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Advanced Coal Wind Hybrid: Economic Analysis

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Acronyms and Abbreviations

ACWH	advanced coal-wind hybrid
CC	combined cycle power plant
CCGT	natural gas combined cycle gas turbine power plant
CCS	carbon capture and storage
CT	combustion turbine
EOR	enhanced oil recovery
Fuel production	production of liquid fuels such as synthetic crude
G+CC+CCS	gasification combined cycle power plant with carbon capture and sequestration used in the ACWH
IGCC+CCS	stand-alone integrated gasification combined cycle power plant with carbon capture and sequestration
FT	Fischer-Tropsch facility to convert synthetic gas into liquid fuels
HVAC	high voltage alternating current transmission
HVDC	high voltage direct current transmission
IGCC	integrated gasification, combined cycle power plant
PC	pulverized coal power plant

Executive Summary

Growing concern over climate change is prompting new thinking about the technologies used to generate electricity. In the future, it is possible that new government policies on greenhouse gas emissions may favor electric generation technology options that release zero or low levels of carbon emissions. The Western U.S. has abundant wind and coal resources. In a world with carbon constraints, the future of coal for new electrical generation is likely to depend on the development and successful application of new clean coal technologies with near zero carbon emissions.

This scoping study explores the economic and technical feasibility of combining wind farms with advanced coal generation facilities and operating them as a single generation complex in the Western US. The key questions examined are whether an advanced coal-wind hybrid (ACWH) facility provides sufficient advantages through improvements to the utilization of transmission lines and the capability to firm up variable wind generation for delivery to load centers to compete effectively with other supply-side alternatives in terms of project economics and emissions footprint. The study was conducted by an Analysis Team that consists of staff from the Lawrence Berkeley National Laboratory (LBNL), National Energy Technology Laboratory (NETL), National Renewable Energy Laboratory (NREL), and Western Interstate Energy Board (WIEB).[1]

We conducted a screening level analysis of the economic competitiveness and technical feasibility of ACWH generation options located in Wyoming that would supply electricity to load centers in California, Arizona or Nevada.[2] Figure ES-1 is a simple stylized representation of the configuration of the ACWH options. The ACWH consists of a 3,000 MW coal gasification combined cycle power plant equipped with carbon capture and sequestration (G+CC+CCS plant)[3], a fuel production or syngas[4] storage facility, and a 1,500 MW wind plant. The ACWH project is connected to load centers by a 3,000 MW transmission line. In the G+CC+CCS plant, coal is gasified into syngas and CO_2 (which is captured). The syngas is burned in the combined cycle plant to produce electricity. The ACWH facility is operated in such a way that the transmission line is always utilized at its full capacity by backing down the combined cycle (CC) power generation units to accommodate wind generation. Operating the ACWH facility in this manner results in a constant power delivery of 3,000 MW to the load centers, in effect firming-up the wind generation at the project site.

[1] A Steering Committee, consisting of a diverse group of stakeholders and technical experts, was also convened to review and provide feedback on the project's approach and results.

[2] We consider a transmission line from southern Wyoming to southern California via southern Nevada as a representative transmission line for estimating transmission costs for generation options located in Wyoming. A transmission line from southern Wyoming to load centers in Arizona via southern Nevada will have similar costs; hence we do not analyze this transmission option separately.

[3] The G+CC+CCS coal plant in the ACWH is very similar to an integrated gasification combined cycle coal plant equipped with CCS (IGCC+CCS) except unlike an IGCC+CCS plant, the G+CC+CCS plant is connected to a fuel production or a syngas storage facility.

[4] Gas produced from the gasification of coal.

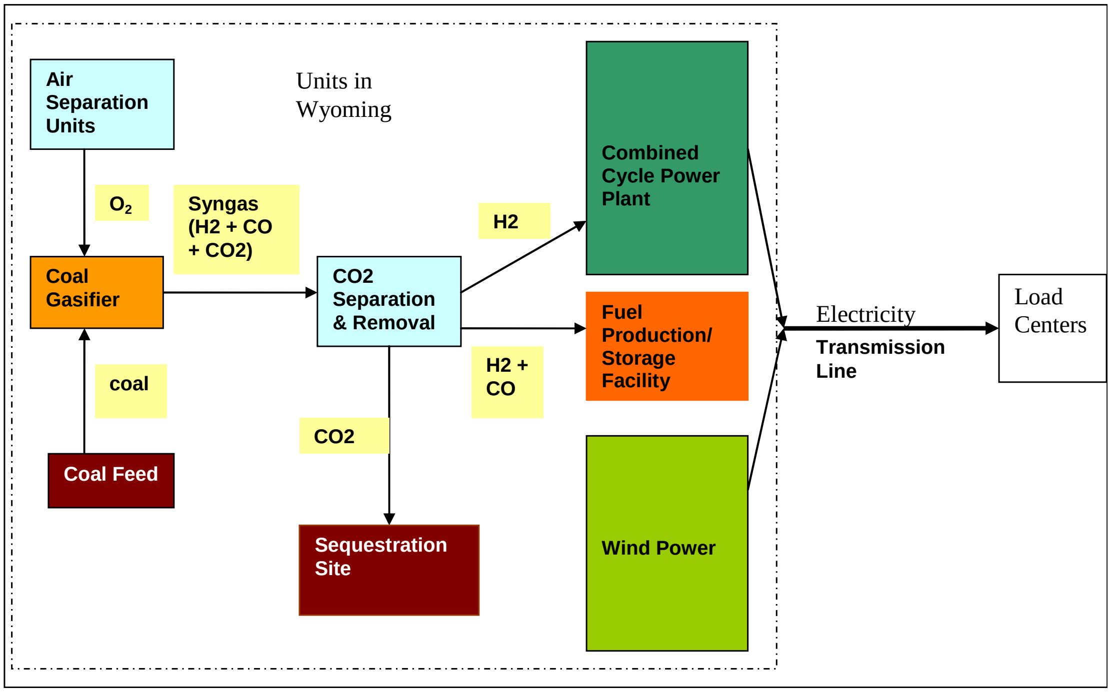

Figure ES-1. Advanced Coal Wind Hybrid: Basic Configuration

In terms of approach, we first reviewed and analyzed several different ACWH configurations (see yellow boxes in Figure ES-2) in order to establish a preferred ACWH option (shown as orange box in Figure ES-2). Second, we analyzed the net benefits of a hybrid configuration for this preferred ACWH option (i.e. benefits outweigh costs) by comparing it with a benchmark advanced coal-wind non-hybrid facility.

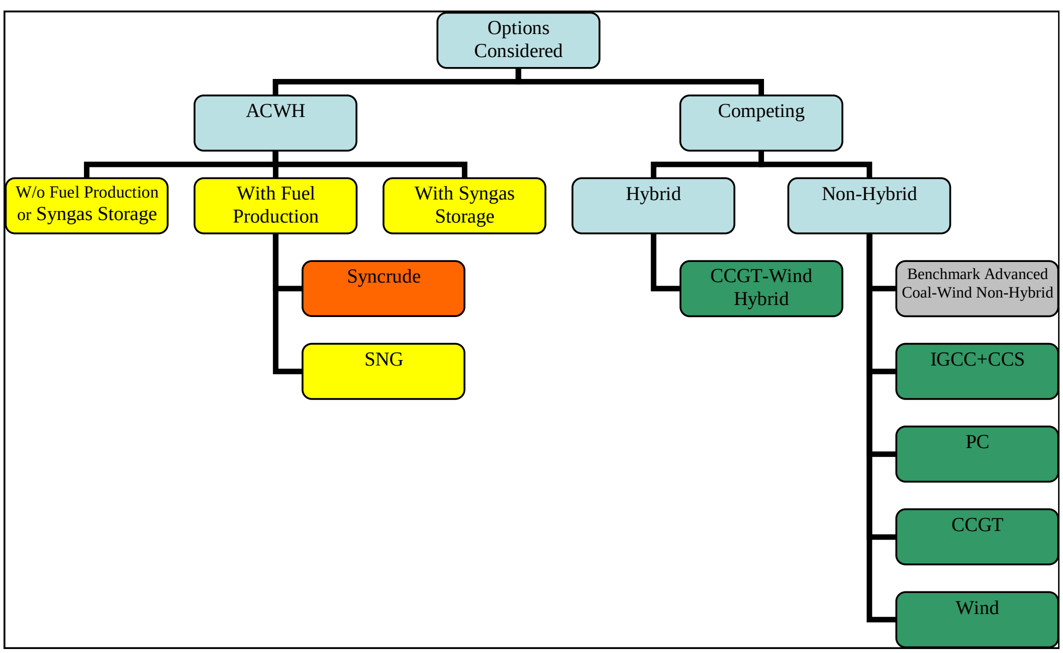

Figure ES-2. ACWH and Competing Options

Note: The preferred ACWH option is shown in orange box; other ACWH options that were considered are shown in yellow boxes. Competing hybrid and non-hybrid options (to which the preferred ACWH option is compared) are shown in green boxes.

Third, we then compared the levelized cost of electricity delivered to the load center for the preferred ACWH option with other competing hybrid and non-hybrid options, which includes generation, transmission, and emission allowance costs (see green boxes in Figure ES-2). We adjust the levelized cost estimates to take into account the effect of differences in firm capacity, integration costs incurred by variable generation resources (e.g. wind) and the effect of incorporating a fuel production or a syngas storage facility in the ACWH configuration. We assume that the new plants and transmission will be operational in 2015, and our analysis goes through 2045. However, our estimates of costs (e.g., capital costs) of the ACWH and competing options are based on current (2007) costs, given the significant uncertainties associated with projecting future costs of competing generation technologies, particularly for technologies that do not have a long commercial track record.

Comparison among ACWH Options

We analyze two ACWH options with a fuel production facility (i.e., a syncrude production facility or a synthetic natural gas (SNG) production facility) and an ACWH configuration with a syngas storage facility. We find that adding a fuel production or a syngas storage facility improves the utilization of the capital-intensive G+CC+CCS plant compared to an ACWH configuration without either of these options, as evidenced by the lower total adjusted levelized cost of electricity (e.g. ~$73 vs. $77/MWh) [see Table ES-1].

Table ES-1. Total Adjusted Levelized Electricity Cost of ACWH Options and the Benchmark Advanced Coal-Wind Non-Hybrid Facility

	ACWH Configurations				Benchmark Advanced Coal-Wind Non-Hybrid Facility
	without Fuel Production or Syngas storage	With Syncrude Production	with SNG Production	with Syngas Storage	
Total Adjusted Levelized Electricity Cost ($/MWh)	77.5	72.9	72.8	72.8	75.4
Levelized Cost of Fuel Production[5]		$60/bbl	$7.25/MMBtu		

Our analysis also suggests that differences in the levelized costs of electricity among ACWH options with a fuel production or a syngas storage facility are minor. Moreover, our analysis suggests that the ACWH option with a syncrude production facility is more profitable than an ACWH plant with a SNG production facility, given the relative cost of fuel production and fuel prices (see Table ES-1).[6] We select the ACWH option with a syncrude production facility as the preferred ACWH option in the screening level analysis (shown in orange box in Figure ES-2) which we compare to other non-ACWH competing options. If projections of fuel prices change substantially and expected fuel prices during 2015-45 are below the cost of syncrude or SNG production, then the ACWH with a syngas storage facility will be the preferred option.[7]

The Net Benefit of the Preferred ACWH Option

One objective of this study was to assess the net benefits of configuring wind and advanced coal in a hybrid project instead of operating them in a stand-alone manner at a remote location. To analyze these benefits requires a comparison of an ACWH facility

[5] The levelized cost of fuel production in the ACWH configuration is equal to that from a stand alone fuel production facility, because we allocate the extra cost of fuel production due to a lower utilization of the fuel production facility in the ACWH configuration to the cost of electricity generation.

[6] Although the current oil price is below $60/bbl, the current price (on 11/23/2008) of oil futures for all months in 2015 is above $80/bbl (about $70/bbl in 2007 $) which is when we assume that the ACWH will begin operation. The average current price of natural gas futures in 2015 is $8/MMBut (about $7/MMBtu in 2007 $).

[7] The results of comparing levelized cost of electricity of the currently preferred ACWH option (ACWH with syncrude production) with other competing non-ACWH options will be almost identical if the preferred ACWH option is an ACWH with a syngas storage facility. This is because the levelized costs of electricity among ACWH options with a fuel (syncrude or SNG) production or a syngas storage facility are comparable.

with a benchmark advanced coal-wind non-hybrid facility that includes both wind and advanced coal, with each operated in a stand-alone (non-hybrid) manner. In essence, we were interested in assessing the specific benefits that come from joint optimization of wind and advanced coal plant in a hybrid configuration (i.e. whether the savings in transmission, wind integration, and wind resource adequacy costs would outweigh the increased fixed costs per unit of power generation and fuel production, given the lower utilization factor of the power generation and fuel production units in the ACWH configuration).

For our base case assumptions, we found that the levelized costs of the ACWH facility were about $2.5/MWh lower (or 3.5%) than a benchmark advanced coal-wind non-hybrid facility (see Table ES-1). This translates into a net benefit of about $860 million over the life of the project. Although the net benefits are modest, we also found that they are relatively insensitive to variations in key input parameters.

Comparison of the Preferred ACWH Option with Hybrid and Non-hybrid Alternatives

We compared the preferred ACWH option with other hybrid and non-hybrid options using our base case assumptions and also analyzed the sensitivity of our results to changes in the values for key performance characteristics or inputs (e.g. natural gas prices, emission allowance prices, wind capacity factor, EOR revenues, and technology costs). We also calculated the break-even values for several key inputs at which the ACWH option becomes more economical than a competing option (see Table ES-2). The competing options include: a CCGT-wind hybrid plant, a stand-alone wind plant, a stand-alone IGCC+CCS coal plant, and a stand-alone pulverized coal (PC) plant, all located in Wyoming, and a combined cycle gas turbine (CCGT) plant located near the load center (see Figure ES-2). Based on our screening level analysis, the ACWH is quite competitive with other generation technologies using our base case assumptions (see Table ES-2). The ACWH has a total adjusted levelized cost (TALC) of $73/MWh vs. $92/MWh for a CCGT-wind hybrid, $83/MWh for a CCGT, and $87/MWh for a PC plant. The TALC of the ACWH plant (i.e. $73/MWh) is also comparable or slightly less than the TALC of a stand-alone IGCC+CCS coal ($75/MWh) and wind facility ($78/MWh) under our base case assumptions. Our analysis does not take into account the difference in the level of risk associated with the cost of these options (e.g.,, wind plants are a more proven technology than advanced coal plants and hence their cost estimates are more reliable). In this context, we argue that the advantages of the ACWH over wind are not as significant given the relatively small difference in the cost of these options.

Table ES-2. Comparison of the Preferred ACWH Facility and Competing Options

	ACWH	CCGT-Wind Hybrid	CCGT	PC	Wind	IGCC+CCS
Base Case						
Total Adjusted Levelized Cost of Electricity ($/MWh)	73	92	83	87	78	75
Break-Even Analysis of ACWH and Competing Options						
Competing Option Compared with the ACWH		**CCGT-Wind Hybrid**	**CCGT**	**PC**	**Wind**	**IGCC+CCS**
Sensitivity Parameter		NG Price ($/MMBtu)	NG Price ($/MMBtu)	CO2 Price ($/ton CO_2)	Wind Cap. Factor (%)	EOR Revenues ($/MWh)
Base Case Value		7.3	7.3	40	47	8
Break-Even Value*		3.7 ↑	5.7 ↑	23 ↑	52 ↓	16 ↓

Note: TALC is estimated in 2007 real dollars

* Value of the sensitivity parameter above or below which (indicated by the direction of the arrow) the ACWH option becomes more economical that the competing option (with all other assumption at their base case value).

We also analyze the competitiveness of the ACWH option with other options under different assumptions for key input parameters (e.g., natural gas and emission allowance prices). We calculated "break-even" values for key input parameters which provide insight on the circumstances in which the ACWH will be a preferred option. For example, with our base case assumption of emission allowance price ($40/ton of CO_2), the ACWH will be more economical than a CCGT-wind hybrid if the levelized natural gas price during 2015-45 is above $3.7/MMBtu (which is referred to as the break-even value of the natural gas price in Table ES-2). Although natural gas prices in Wyoming have historically been somewhat lower than other parts of the West, we expect that the natural gas price in Wyoming will be significantly more than $3.70/MMBtu; hence, the ACWH is likely to be more economical than a CCGT-wind hybrid under most circumstances. Similarly, our results suggest that the ACWH is more economical than a CCGT plant located near the load center if natural gas prices are above $5.7/MWh. This break-even natural gas price is 17% lower than that assumed for the base case.

We also find that the ACWH is more economical than a pulverized coal plant in Wyoming if the levelized emission price during 2015-45 is above \$23/ton of CO_2. We find that the ACWH is more economical than a stand-alone IGCC+CCS plant if the enhanced oil recovery (EOR) revenues from the sequestration of CO_2 captured are less than \$16/MWh, which is likely to be the case given the limited EOR potential in the West relative to the amount of CO_2 captured.

The benefits of the ACWH over the stand-alone wind generation option increase with increased transmission, wind integration, and resource adequacy costs. Wind generation costs are also significantly influenced by the wind capacity factor, because it affects both the per unit costs of wind generation and transmission. For example, if the wind capacity factor is 40% (rather than 47% used in our base case), the ACWH is even more economical than the stand-alone wind generation option. Conversely, if the wind capacity factor is above 53%, the ACWH does not offer an advantage over stand-alone wind generation.

Given the capital intensity of the ACWH option, the estimated capital costs to build an ACWH plant have a significant impact on its economic competitiveness, particularly compared to less capital-intensive and mature technologies such as a CCGT. For example, if the capital cost of the ACWH and CCGT are each 20% higher than that assumed for the base case, the benefits of the ACWH over CCGT are reduced drastically.

Our results suggest that a more detailed economic analysis of an ACWH project may be worthwhile given that this option appears competitive in our screening level analysis for both base case assumptions and sensitivity analysis. The ACWH also can be considered a "clean" generation option given that its CO_2 emissions footprint is much less than a CCGT or pulverized coal plant of equivalent capacity (i.e. CO_2 emissions are only about 15% and 7% of a CCGT and a PC plant respectively).

It is also important to note several major caveats to the findings of this scoping study. First, there is limited empirical basis for the estimates of the costs of an advanced coal plant, since they have not yet been commercially built. If the actual costs of these plants are significantly higher than our assumed cost values, the results of our screening level analysis would change significantly. Second, there are many technical, environmental, and regulatory issues surrounding large scale carbon capture and sequestration which have not been resolved yet and could affect the feasibility of the ACWH option. Third, our results are based on a screening level analysis which does not fully account for the impacts and interaction of large new generation projects with existing utility systems that are typically accounted for as part of a resource planning and capacity expansion modeling effort.

1. Introduction

Growing concern over climate change is prompting new thinking about the technologies used to generate electricity. In the future, it is possible that new government policies on greenhouse gas emissions may favor electrical generation technology options that release zero or low levels of carbon emissions.

The West has abundant wind and coal resources. Wind energy is an emerging resource that could provide a significant amount of electricity if fully developed. Coal is a significant source of existing generation and contributed 39% of the net generation in 2004 in the states of the Western Governors' Association.[8] In a world with carbon constraints, the future of coal for new electrical generation is likely to depend on the development and successful application of new clean coal technologies with near zero carbon emissions.

This scoping study explores the economic and technical feasibility of combining wind farms with advanced coal generation facilities and operating them as a single generation complex. The key questions examined are whether an advanced coal-wind hybrid (ACWH) facility provides sufficient advantages through improvements to the utilization of transmission lines and the capability to firm up variable wind generation for delivery to load centers to compete effectively with other supply-side alternatives in terms of project economics and emissions footprint.

To explore these issues, we conduct a screening level technical and economic analysis of an ACWH option located in Wyoming that supplies power to load centers in California, Arizona, or Nevada.[9] The advanced coal plant included in the hybrid configuration is equipped with carbon capture and sequestration (CCS) which captures over 90% of the CO_2 emitted. We also assume that a large wind project is co-located and developed at a site that is near the advanced coal plant. The net CO_2 emission rate from this ACWH plant configuration is less than 15% of that from a natural gas combined cycle gas turbine (CCGT) plant.

The study was conducted by an Analysis Team that consists of staff from the Lawrence Berkeley National Laboratory (LBNL), National Energy Technology Laboratory (NETL), National Renewable Energy Laboratory (NREL), and the Western Interstate Energy Board. A Steering Committee, consisting of a diverse group of stakeholders and technical experts, was also convened to review and provide feedback on the feasibility study's approach and results. The potential audiences for the study include policymakers, public utility commissions, load serving entities and developers of major

[8] Report of the Clean and Diversified Energy Advisory Committee: Clean Energy, A Strong Economy and a Healthy Environment, Western Governors' Association, June, 2006, p. 1 (CDEAC Report) (citing Energy Information Administration, 2004 EIA Annual Power Plant Report).

[9] We consider a transmission line from southern Wyoming to southern California via southern Nevada as a representative transmission line for estimating transmission costs for generation options located in Wyoming. A transmission line from southern Wyoming to load centers in Arizona via southern Nevada will have similar costs; hence we do not analyze this transmission option separately.

transmission projects that will be influencing the choice of generation and transmission options for the West over the next decade.

We used a spreadsheet-based model to undertake three types of screening level economic analysis. First, we reviewed and analyzed several different ACWH configurations in order to establish a preferred ACWH option. Second, we analyzed the net benefits of a hybrid configuration for this preferred ACWH option to evaluate if the benefits outweigh the costs of a configuration strategy by comparing it with a benchmark advance coal-wind non-hybrid facility. We then compared the preferred ACWH option with other competing hybrid and non-hybrid options. We consider only a limited number of competing generation options since the primary objectives of this feasibility study are to analyze and compare the economics of an ACWH generation option with common alternatives. We also conduct sensitivity analysis to assess the extent to which the competing supply-side options are influenced by assumptions for key inputs such as the cost of CO_2 emission allowances and natural gas prices.

In terms of economic metrics, we compare the levelized cost of electricity delivered to the load center from the hybrid plant as well as other generation options. In estimating levelized costs, we include the cost of generation, transmission, and emission allowances and take into account the effect of the difference in the firm capacity of each option and integration costs incurred by variable resources. This screening level analysis is not a substitute for a system-wide production cost and/or capacity expansion modelling study. The remainder of the report is organized as follows:

In **Section 2,** we describe the underlying economic rationale for an ACWH generation option and discuss the rationale for choosing the specific hybrid configuration used in our Base Case analysis. In **Section 3**, we describe the full set of ACWH and competing hybrid and non-hybrid generation options considered in this analysis. In **Section 4**, we describe the analytical approach used to compare ACWH and competing options. In **Section 5**, we summarize cost estimates and technical parameters for various generation options. In **Section 6**, we present the results of the economic analysis and discuss circumstances under which ACWH options may have economic merit and are competitive with other generation options. In **Section 7** we compare the emission footprint of ACWH and other competing options.

2. Economic Rationale for an ACWH Generation Option in Wyoming

In this section, we describe the basic configuration and the operation of the ACWH generation option and explain the economic rationale for the project. Our objective is to convey the economic intuition behind the ACWH configuration by exploring its potential benefits and costs.

At a conceptual level, we evaluate an ACWH option located in Wyoming because Wyoming has large quantities of high quality wind (class 6 and above) suitable for wind generation, abundant and relatively inexpensive coal resources, and a geology that is suitable for carbon storage. Wyoming is also distant from load centers in California, Arizona, and Nevada and hence improving transmission utilization, the primary benefit of the ACWH option, has more economic value given the high cost of long distance transmission lines.

Figure 1 is a simple stylized representation of the configuration of an ACWH project located in Wyoming. The ACWH consists of a 3,000 MW coal gasification, combined cycle power plant equipped with carbon capture and sequestration (G+CC+CCS)[10], a fuel production or a syngas storage facility, and a 1,500 MW wind plant. The project is connected to load centers in Arizona, California, or Nevada by a 3,000 MW transmission line. In the G+CC+CCS plant, coal is gasified into syngas (a mixture of hydrogen dioxide and carbon monoxide) and CO_2 which is separated from the syngas and captured. The syngas is burned in the combined cycle plant to produce electricity.

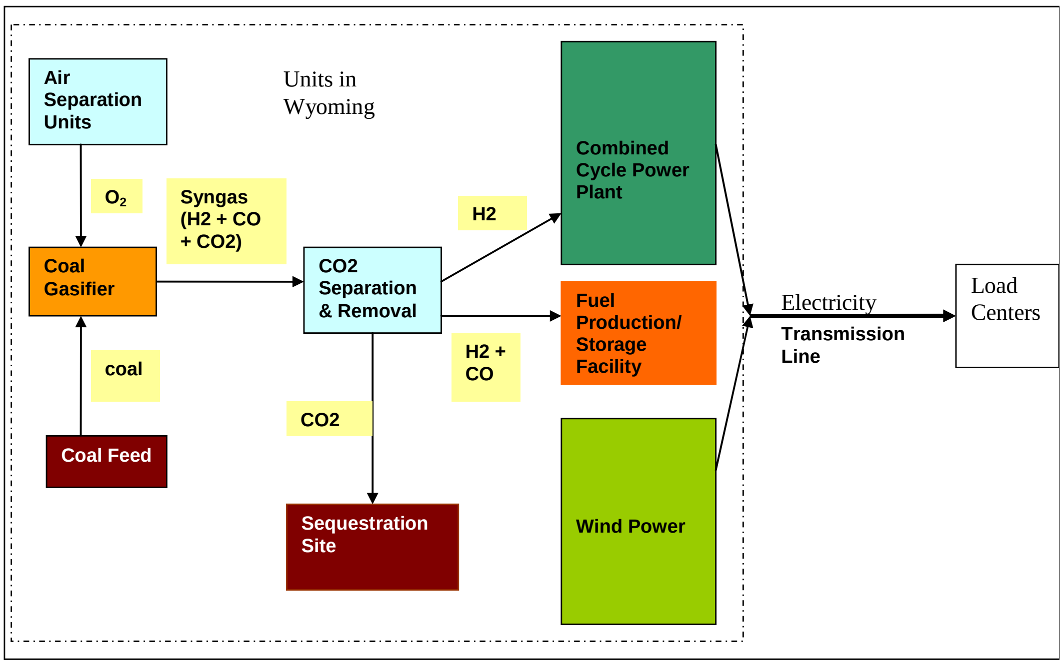

Figure 1. Advanced-Coal Wind Hybrid: Basic Configuration

[10] The G+CC+CCS plant in the ACWH is very similar to an integrated gasification combined cycle power plant with CCS (IGCC+CCS). However, unlike an IGCC+CCS plant, the ACWH is connected to a fuel production or syngas storage facility.

The ACWH facility is operated in such a way that the transmission line is always utilized at its full capacity. When the wind generators are not producing power, the power generation units in the ACWH are operating at their full capacity (i.e., producing 3,000 MW) and fully utilizing the transmission line. When the wind generators are producing power, the power generation unit (CC) in the G+CC+CCS plant is backed down to accommodate wind generation and the net power output is maintained at 3,000 MW. During this operational mode, the gasifiers and other parts of the G+CC+CCS plant are operating at their full capacity because the syngas that is not used for power generation is either stored or used for fuel production. When the wind power output drops, the power generation units in the G+CC+CCS plant are ramped up to maintain the net output from the ACWH at 3,000 MW so that the transmission line is utilized at its full capacity.[11]

We choose a G+CC+CCS coal plant in the ACWH configuration because it will meet the current and future climate regulations in the load centers and it can also change its output fast enough (cycle) to accommodate wind generation, unlike a pulverized coal plant.[12] Moreover, carbon capture is relatively less expensive in a coal gasification, combined cycle power plant compared to a pulverized coal plant.

The G+CC+CCS plant is highly capital intensive and is typically suitable for baseload operation. Combining it with a wind resource in a hybrid configuration would require that it be operated at a lower capacity factor than typical operation of a G+CC+CCS plant. Given the capital intensity of the G+CC+CCS plant, it may not be economical to lower its utilization to improve the utilization of transmission lines. To address this issue, we included a fuel production or a syngas storage facility in the ACWH which improves the utilization of the G+CC+CCS plant as follows. In a G+CC+CCS plant, the capital cost of the power generation unit (CC) is only about 25% of its total capital cost. The remaining capital costs consist primarily of the cost of air separation units, gasifiers, pollution control equipment, and CO2 separation and capture equipment. With either a syngas storage or a fuel production facility in the ACWH, only the power generation unit in the ACWH needs to be backed down to accommodate wind generation because the syngas that is not used for power generation can either be stored or used for fuel production.

Although this ACWH configuration with a fuel production or syngas storage facility improves the capacity utilization of a large part of the G+CC+CCS plant, it also has additional costs. If the syngas is stored, costs are incurred for storage. If the syngas is used to produce other fuels, the capacity utilization of the fuel production plant is lower than that of a stand alone fuel production plant.

In Table 1, we briefly summarize some of the key benefits and costs of the ACWH configuration (see Appendix A for a more detailed discussion).

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[11] The economics of the ACWH facility can be further improved by optimizing power and fuel production depending on the relative market prices of fuel and power. However, analyzing the economic impact of such operation of the ACWH is beyond the scope of this analysis.

[12] We find that power generation and fuel production units can cycle fast enough to accommodate wind generation (See Appendix F)

Table 1. Benefits and Costs of the ACWH Configuration

Benefits	Costs
• Improved utilization of transmission lines compared to a wind generation only case because the advanced coal plant in the ACWH is cycled to accommodate wind generation and the transmission line capacity is fully utilized • ACWH avoids wind integration costs compared to a case in which only wind generation is added to the system; the power output from the ACWH is similar to that of a dispatchable baseload resource • Higher capacity contribution towards meeting resource adequacy requirements compared to stand-alone wind generation; wind generation in the ACWH is firmed up at the project site	• Higher fixed cost per unit of generation output compared to a stand-alone IGCC+CCS plant due to lower utilization of the power generation units in the ACWH because they need to be backed down to accommodate wind generation leading to lower utilization • Higher fixed cost per unit of fuel production compared to a stand-alone fuel production facility due to lower utilization; the fuel production facility in the ACWH is supplied with syngas only to the extent it is not utilized by the power generation units when they are backed down to accommodate wind generation • Higher heat rate of the G+CC+CCS plant in the ACWH compared to a stand alone IGCC+CCS plant because it operates at partial load in more hours

3. Hybrid Configurations and Competing Options

In this section, we discuss several different ACWH options and other competing options considered in this analysis (see Figure 2).

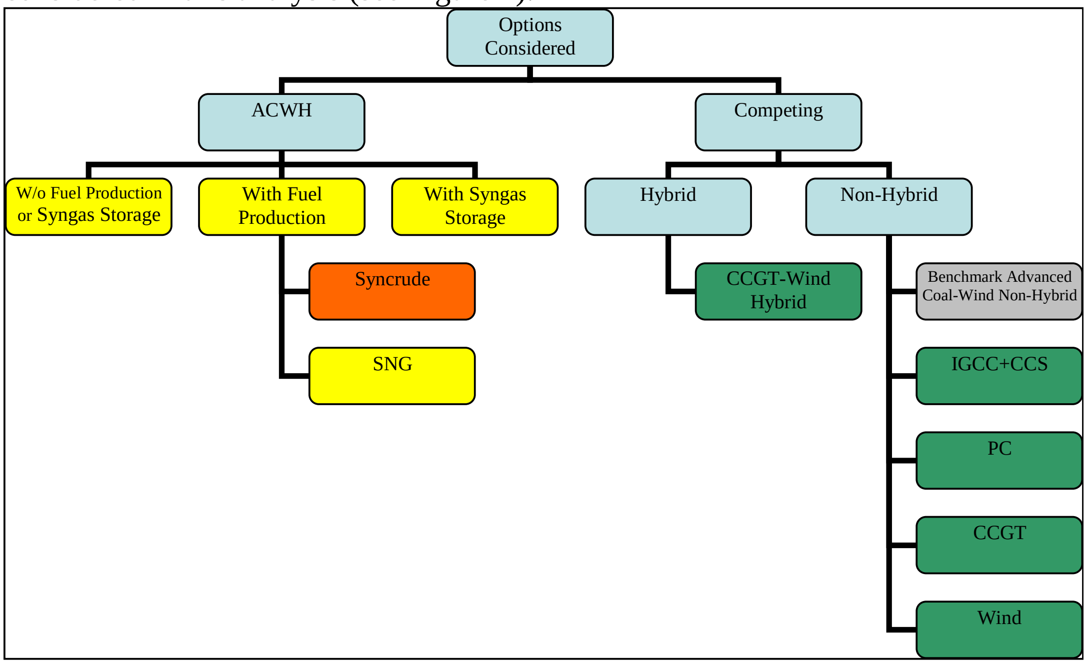

Figure 2. ACWH and Competing Options

Note: The preferred ACWH option is shown in orange box; other ACWH options that were considered are shown in yellow boxes. Competing hybrid and non-hybrid options (to which the preferred ACWH option is compared) are shown in green boxes.

All ACWH options include a 3,000 MW, G+CC+CCS coal plant and a 1,500 MW wind plant. In addition, some ACWH options include a fuel production or a syngas storage facility. All the non-hybrid competing options are also rated at 3,000 MW. Options located in Wyoming are connected to load centers in California, Arizona, or Nevada by a 3,000 MW transmission line. Appendix C describes the rationale for selecting ACWH and competing options with a particular capacity.

3.1 ACWH Options

We analyze an ACWH option in which there is neither a syngas storage nor a fuel production facility as a benchmark to evaluate the benefits of adding these facilities to the ACWH configuration (see yellow box in Figure 2). Adding a syngas storage or a fuel production facility allows the backing down of only the power generation units (whose capital cost is about 25% of the capital cost of the G+CC+CCS plant) to accommodate wind output. The rest of the G+CC+CCS plant is fully utilized and is not backed down. We consider two options for fuel production facilities: a syncrude facility and synthetic natural gas (SNG) facility. For the ACWH configuration with a syncrude production facility, the syncrude produced is expected to be sold to refineries for further processing. For the ACWH configurations with a SNG facility, we assume that the SNG facility will produce pipeline quality gas that will be transported through a pipeline which connects the SNG production facility to the nearest natural gas hub.

An ACWH configuration with a syngas storage facility is the other option for allowing the backing down of only the power generation units for accommodating wind output. In this configuration, all the other components of the G+CC+CCS plant are sized lower than the power generation unit. The gasifiers (and other components) are operated at their peak capacity most of the time and produce enough syngas (over time) to power a 3000 MW power generation unit operating at about 70% capacity factor.[13] Whenever the power output from the G+CC+CCS plant needs to be more than 2,295 MW (i.e., when the wind plant is producing below its average output of 705 MW), the cleaned up syngas from a storage facility will be utilized for powering some of the generation capacity. For example, if the power plant is operating at 3,000 MW (which is the case when the wind output is zero), the syngas for producing 2,295 MW is provided by the gasifiers and the syngas required to power the remaining 705 MW is obtained from the storage facility. Alternatively, whenever the power generation unit is producing below 2,295 MW, the syngas gas not utilized for power generation is stored. With this configuration, only the power generation unit needs to be backed down to accommodate wind generation and the rest of the plant is utilized at its full capacity. The amount of syngas storage required in this option is influenced by the variation in wind output. See Appendix D for the discussion of the procedure used for estimating the syngas storage requirement and its cost.

3.2 Competing Options

We also considered a limited number of competing generation options in this scoping study (see Appendix B for the rationale for including certain options while excluding others). We made a conscious choice not to evaluate energy efficiency as a resource in this study for several reasons: (1) we assume that total resource costs for most energy efficiency measures/programs will be significantly less than the hybrid and competing options considered in this study, (2) that utilities will acquire cost-effective energy efficiency resources, and (3) that even if utilities acquire all cost-effective energy efficiency, there is some residual resource need that will be met by supply-side options in a carbon-constrained world.

We analyzed several other hybrid options, including a CCGT-wind hybrid and a combustion turbine (CT)-wind hybrid option. These hybrid options essentially involve a CCGT or a CT power plant that is cycled with wind generation. We also examined a number of traditional supply-side options that could be located in Wyoming: a conventional pulverized coal (PC) plant, a wind plant,[14] and a stand-alone advanced coal

[13] If we assume that one unit of gas is required to generate 1 GWh, a 3,000 MW plant operating at 70% capacity factor will need 18,396 units of gas. Hence the gasifiers (which have 85% availability) need to have a capacity equivalent to 2,470 MW to produce the same amount of syngas.

[14] For the stand-alone wind generation option, we assume that the wind capacity will be overbuilt by 20% compared to the capacity of the transmission lines to improve their utilization (see Appendix C for the rationale and detailed analysis of overbuilding wind capacity).

plant (IGCC+CCS) [see green boxes in Figure 2]. For these options, we include the cost of a transmission line which connects them to load centers in California, Nevada, and Arizona. We also consider a CCGT plant as the primary alternative for locating generation near the load center. This generation option is assumed to have transmission costs equivalent to 100 miles of lines. All options that utilize fossil fuels and produce CO2 are assumed to buy emission allowance permits for the amount of CO2 produced.

4. Analytic Approach

In this section, we describe the analytic approach used to conduct our screening level economic analysis of ACWH and competing options. As shown in Figure 3, we first compare among different ACWH options to determine the preferred ACWH option. We then analyze the net-benefit of a hybrid configuration[15] for this preferred ACWH option by comparing it with a benchmark advanced coal-wind facility where the coal and wind plants are operated in a stand-alone (non-hybrid) manner. Finally, we compare the preferred ACWH option with other competing supply side options

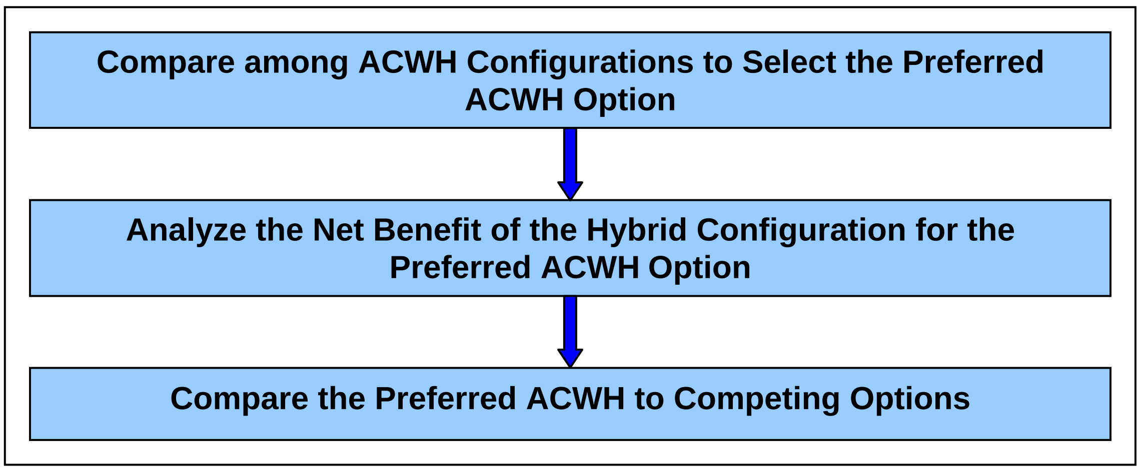

Figure 3. Key Analysis Steps

We used levelized cost at the load center as the metric for this economic, screening level analysis. However, we make several adjustments to the standard method of calculating levelized cost for two reasons: (1) to address the limitations of comparing dispatchable baseload and variable generation options based on levelized costs and (2) to account for the effect of incorporating a fuel production or a syngas storage facility in the ACWH configuration (see Figure 4 for adjusted levelized cost method).

[15] The benefit of hybridization is the benefit of the joint optimization of the advanced coal and wind plant operations instead of operating them as stand-alone facilities.

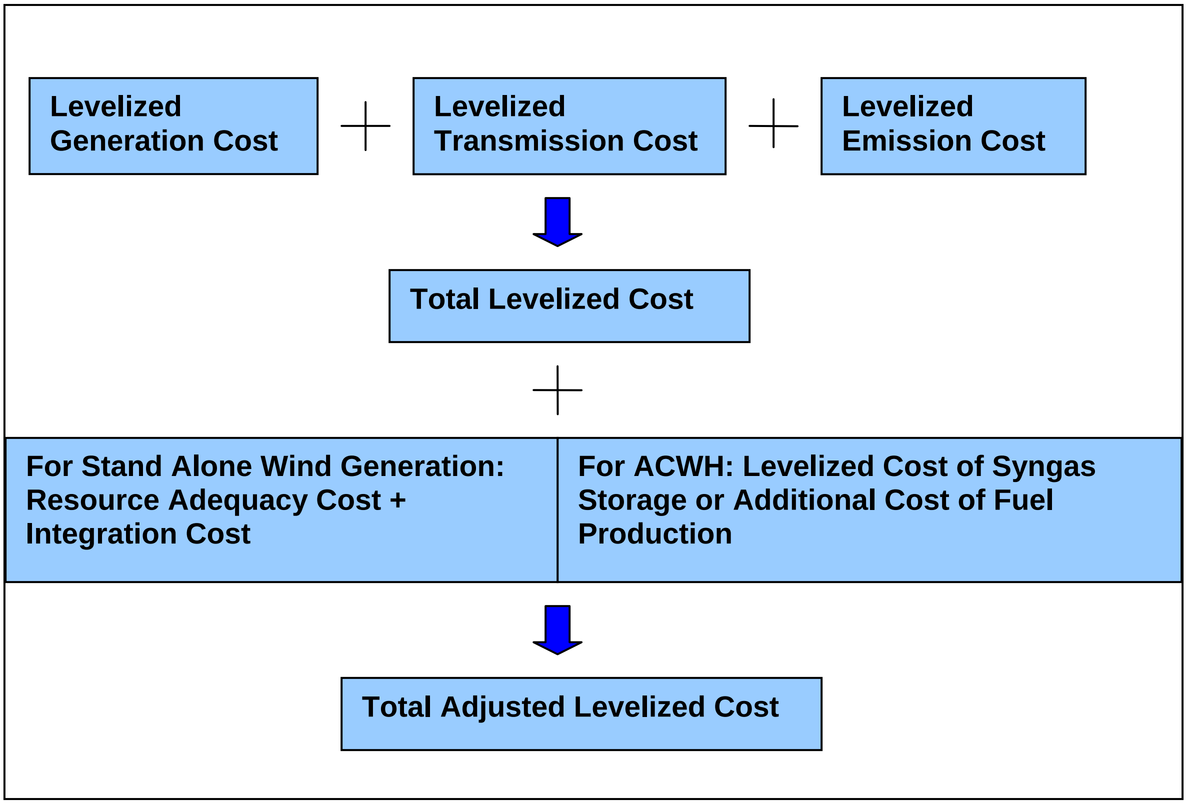

Figure 4. Estimating Adjusted Levelized Cost

4.1 Adjustments to the Levelized Cost Estimates

Using levelized costs to compare the economics of competing generation options has a number of limitations because it does not account for the following factors.

- The difference in the contributions made by competing resources towards meeting resource adequacy requirements. This is an important issue when comparing variable generation resources (e.g., wind) to baseload dispatchable resources because wind resources contribute lesser capacity towards meeting resource adequacy requirements than that contributed by baseload dispatchable resources.
- Accounting for the timing of generation which influences its value (i.e. generation during peak hours is more valuable than generation during off-peak hours).
- Integration costs imposed by variable generation resources (e.g., wind) on the system.

We address these limitations as follows.

1. We add a capacity cost to the levelized cost of electricity in the case of a stand-alone wind generation option. This cost is based on the cost of the additional capacity required to make the capacity contributions towards meeting resource adequacy (or capacity) requirements per unit of electricity produced by wind equivalent to other baseload

options. The cost of additional capacity is based on the capital cost of a CT. The additional capacity requirement (ACR) is estimated as follows:

$$ACR = CC_{baseload} - CC_{wind}$$

where,

$CC_{baseload} =$ Capacity contributions by a baseload dispatchable resource that produces the same amount of electricity as the wind plant

$CC_{wind} =$ Capacity contributions by a wind plant.

It is important to note that we are not estimating the resource adequacy (or capacity) cost by estimating the capacity cost of firming up the wind generation one to one.[16]

2. Given the wind generation profile of Wyoming wind over a year, we find that the time of use value of wind generation is very similar to a baseload resource (see Appendix E for more details). Hence, in comparing wind with other options for meeting baseload requirements, we do not find it necessary to adjust levelized costs to reflect their time of use value.

3. We add wind integration cost to the levelized cost of wind generation to take into account the costs imposed by its variable generation on the system.

Some of the ACWH configurations include syngas storage or fuel production facilities for improving the utilization of the ACWH. These facilities also impose certain costs.

For the ACWH configuration with syngas storage, we add the cost of storage to the levelized cost of electricity. For the ACWH configurations with fuel production facilities, we add the share of fuel production facility costs that should be allocated to electricity generation from the ACWH (vs. those that can be assigned to fuel production). The share of fuel production facility cost allocated to the cost of electricity generation is the

[16] If this approach is taken, the resource adequacy (or capacity) cost is much higher than our approach. However, with this approach, the capacity contributed by the wind resource with the backup is about twice per unit of electricity generated compared to a baseload dispatchable plant. Thus, this approach inaccurately burdens the wind generation option with the cost of extra capacity beyond what is required to make the capacity contributions per unit of electricity produced by a wind resource equivalent to that of a baseload resource. Other studies (Utility Wind Integration Group 2006) have also found that the wind generation need not be backed up one to one to meet resource adequacy requirements.

additional cost of fuel production facility due to its lower utilization in the ACWH configuration compared to a stand-alone fuel production facility.[17]

We estimate the additional cost of fuel production by calculating the extra capital cost of the fuel production facility in the ACWH compared to a stand-alone fuel production facility which produces the same amount of fuel as the fuel production facility in the ACWH. The extra capital cost is due to a higher capacity requirement of the fuel production facility in the ACWH because the fuel production facility in the ACWH operates at a lower capacity factor. We allocate the additional cost of fuel production to the cost of power generation. Once the extra cost of fuel production due to the lower utilization of the fuel production facility in the ACWH is allocated to the cost of power generation, the economics of fuel production is similar to the economics of fuel production from a stand-alone facility.[18]

To summarize, the total adjusted levelized cost of electricity (TALC) for the ACWH and competing options is estimated as follows.[19]

$TALC = GC + TC + EA + AC + RA + I$

GC = Levelized generation cost

TC = Levelized transmission cost
EA = Levelized emission allowance cost

RA = Levelized resource adequacy cost (applicable only for the stand-alone wind generation option)

I = Levelized integration cost (applicable only for the stand-alone wind generation option)

AC = Levelized additional cost of fuel production or syngas storage (applicable only for the ACWH options with a fuel production or a syngas storage facility)

Table 2 shows the formulas and key inputs used to estimate various components of the total adjusted levelized cost of electricity on a per unit basis.

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[17] This is the case because the fuel production facility in the ACWH receives syngas only to the extent it is not utilized by the power generation units in ACWH when they are backed down to accommodate wind generation.
[18] We estimate the levelized cost of fuel production as if this were from a stand alone fuel production facility.
[19] We exclude NO_X emission costs because generation options are not located in urban air sheds. We also do not include the cost of SO_X allowances because they are relatively low (<$0.5/MWh) even for a PC plant which has relatively high SO_X emissions. We base our assumptions of future SO_X prices on the projections by EIA in its analysis of the McCain-Lieberman bill of 2006 (S280). EIA projects declining SO_X prices in the future which reach a value of zero in 2028 in a scenario where carbon emissions are regulated. This is primarily because in a carbon emission regulation scenario very few new PC plants are projected to be built and a significant amount of the existing PC plants is expected to be taken out of service. Given low SO_X prices, the cost of SO_X emission allowance per MWh are not significant.

Table 2. Components of the Total Adjusted Levelized Cost (TALC)

Components	Estimation	Key inputs
GC ($/MWh)		
Capital Cost	$\frac{TPC \times FCR}{8760 \times CF}$	Total plant capital cost (TPC), capacity factor (CF), fixed charge rate (FCR)[20]
Fixed O&M	$\frac{FCO\&M}{8760 \times CF}$	Fixed O&M cost per year (FCO&M), CF
Fuel Cost	$FP \times HR$	Levelized fuel price (FP), heat rate(HR)
Variable O&M	VO&M	Variable O&M (VO&M)
TC ($/MWh)		
Capital cost	$\frac{TCC \times FCR}{8760 \times TU}$	Transmission capital cost (TCC), transmission utilization (TU), FCR
Fixed O&M	$\frac{TFO\&M}{8760 \times TU}$	Transmission fixed O&M cost per year (TFO&M), TU
Transmission loss cost	$TL \times TALC*$	Transmission losses (TL), TALC* is the TALC excluding the cost of transmission losses
EA ($/MWh)		
Emission allowance (EA)	$CP \times EF$	Levelized carbon price (CP), emission factor (EF):emissions per unit of electricity delivered
Adjustments for variable generation options ($/MWh)		
Resource adequacy (RA) Cost	Estimation method explained in section 4.1	Capacity contributions of a resource, cost of capacity, CF, and FCR
Integration (I)	Based on estimates from wind integration studies	
Adjustments for ACWH with fuel production or syngas storage ($/MWh)		
Additional cost of fuel production or Syngas storage (AC)	Estimation method described in section 4.1	Storage requirement, storage cost, capital cost and utilization of the fuel production facility

Factors other than TALC may also influence the choice between hybrid and competing options, including uncertainty in the cost and performance estimates, natural resource

[20] Fixed charge rate: Fixed charge rate is used to annualize the total capital cost. Fixed charge rate is estimated based on the cost of capital, life of the plant, depreciation schedule, and income taxes.

requirements (e.g., land and water), and regulatory issues. See Appendix G for a qualitative discussion of these factors.

5. Cost and Performance Assumptions for ACWH and Competing Options

In this section, we summarize the key assumptions used to characterize the cost, performance, and operating features of ACWH and competing resource options (see Appendix D for a more detailed discussion).

The ACWH considered in our analysis could be operational by 2015 given the current status of advanced coal technology and the typical lead times required to build power plants.[21] Hence we choose 2015-45 as the time frame of our analysis given that typical power plants last at least 30 years. Our estimates of costs of the ACWH and competing options are based on current (2007) costs.[22] There are significant uncertainties associated with projecting future costs of competing generation technologies, particularly for technologies that do not have a long commercial track record.[23]

Table 3 summarizes the key input parameter assumptions used for competing generation technologies. Although we analyze four ACWH configurations, only a few cost and performance assumptions are different across these options and are stated accordingly in Table 3. Costs and parameter estimates related to fossil fuel-based generation and renewable energy technologies were provided by NETL and NREL respectively.[24] Cost and parameter assumptions for transmission and assumptions related to project financing were based on the assumptions developed by the Western Regional Transmission Expansion Partnership (WRTEP) for the benefit-cost analysis of the Frontier Line possibilities (WRTEP, 2007a and b). These assumptions were reviewed by the Analysis Team and the Steering Committee.

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[21] The time line for the beginning of commercial operation of ACWH options will also depend on the construction of new transmission lines and the time required to obtain regulatory approval for CCS. Because it is difficult to predict these factors, it is possible that ACWH options may not be able to come online by 2015.

[22] We used capital costs for generation technologies as of 2007 because we had reasonably well-documented cost estimates for all technologies. This ignores recent escalation in capital costs of all generation technologies as well as the recent decline in commodity prices due to a global economic slowdown, which may impact the run-ups in costs in 2008. We analyze the sensitivity of our results to capital cost assumptions.

[23] It is unlikely that projected costs in 2015 will be a better estimate of the actual costs during that period than current cost estimates. Moreover, we are primarily interested in the relative competitiveness of generation technologies. The relative costs of different resource options will change only if the recent cost increases are reversed for certain technologies and not for others. There is no prima facie reason to believe that this would be the case.

[24] Capital cost and capacity factor of wind plants are based on AWEA, NREL, and DOE (2007). Wiser and Bolinger (2008) find estimates of capital cost of wind projects installed in 2007 similar to that assumed in this study.

Table 3. Cost and Performance Assumptions

Parameters	**ACWH Configurations**		**Competing Options**			
	G+CC+CCS	Wind	IGCC+CCS	Wind	PC	CCGT
Generation						
Capacity (MW)	3,000	1,500	3,000	3,600	3,000	3,000
Total Plant Cost ($/kW)	3,028	1,723	3,028	1,723	1,915	785
Fixed O&M ($/kW-year)	36	12	36	12	10	26
Variable O&M ($/MWh)	8	5	8	5	5	4.6
Fuel Price ($/MMBtu)	0.55	0	0.55		0.55	7.35
Heat Rate(Btu/kWh)	11,896		11,550		9,100	6,719
Capacity Factor (%) Power generation unit Gasifiers and other system	 70 87[1], 70[2]	 47	 85 85	 47	 90	 90
Life(Years)	30	20	30	20	30	25
EOR revenues – Carbon transport and geologic storage ($/MWh)	0	0	0	0	0	0
Transmission						
Capacity (MW)	3,000		3,000	3,000	3,000	3,000
Cost ($/Million)	3,300		3,300	3,300	3,300	420
Emission Allowance						
Carbon Price ($/Ton CO2)	40	40	40	40	40	40
Emissions (Ton CO2/MWh)	0.056	0	0.056	0	0.830	0.361
Costs related to variable generation						
Integration Cost ($/MWh)	0	0	0	3	0	0
Resource Adequacy Cost ($/MWh)	0	0	0	4.3	0	0
Additional Cost of Fuel Production or the Cost of Syngas Storage ($/MWh)	1.4[3], 1.3[4], 1.3[5]	NA	NA	NA	NA	NA

Notes:
All Cost are in 2007$
1. Capacity factor for gasifiers in the ACWH with fuel production or syngas storage facilities
2. Capacity factor for gasifiers in the ACWH without fuel production or syngas storage facilities
3. Additional cost of syncrude production in the ACWH with a syncrude production facility
4. Additional cost of SNG production in the ACWH with a SNG production facility, and
5. Cost of syngas storage in the ACWH with a syngas storage facility

The cost and performance of the two main components of the ACWH configuration (i.e., the advanced coal plant (G+CC+CCS) and wind plant) are stated separately. For ACWH options, the total plant costs do not include the cost of the fuel production or the syngas storage facilities, as these are estimated separately. See **Appendix D** for additional discussion of key input assumptions.

Generation

Total Plant Cost (TPC)

TPC includes equipment, construction, installation, other miscellaneous costs (e.g., land, engineering, contingency), and interest during construction.[25] TPC estimates for advanced coal and PC plants are for plants located in Wyoming using PRB coal. These costs take into account the effect of higher elevation on capital costs. Capital costs for wind and NGCC plants are generic costs and reflect recent significant increases in capital costs.[26]

Heat Rate

Heat rate estimates for the PC, IGCC+CCS, and G+CC+CCS plants are for power plants located in Wyoming using PRB coal and take into account the effect of higher elevation in Wyoming. The heat rate for the advanced coal plant in the ACWH options (G+CC+CCS plant) is higher than that of an advanced coal plant in the stand-alone coal generation option (IGCC+CCS plant) because the advanced coal plant in the ACWH operates more often at partial load conditions to accommodate wind generation. The heat rate assumed for the CCGT plant is for a generic plant at lower altitude than Wyoming.

[25] NETL provided estimates of the overnight construction cost of fossil generation technologies. Interest during construction was estimated based on utility financing assumptions and typical construction schedules and was added to NETL's estimate of the overnight construction cost to estimate the total plant cost.

[26] For example, MIT (2007) assumes a total plant cost of $1890/kW for an advance coal plant (IGCC+CCS) based on 2001-04 costs while WRTEP (2007a) assumes a total plant cost of $2650/kW based on costs in 2006. Our total plant cost estimate for an advanced coal plant (IGCC+CCS) is $3028/kW, based on 2007 costs.

Capacity Factor

ACWH and competing options are assumed to operate at their maximum capacity factor. For ACWH options without a fuel production or syngas storage facility, the entire G+CC+CCS plant (power generation units as well the gasifiers) need to be backed down to accommodate wind generation; hence the capacity factor is 70% for the gasifiers and the power generation units. We estimate this capacity factor by estimating the extent to which the plant needs to be backed down to accommodate wind generation. In the case of an ACWH configuration with a fuel production or a syngas storage facility, only the power generation units need to be backed down and the gasifiers (and the rest of the system) can continue to run at full capacity; hence their capacity factor is assumed to be 87%.

Fuel Prices

We estimated the levelized price of natural gas during 2015-45 based on a combination of the Energy Information Administration (EIA)'s Annual Energy Outlook (AEO) 2007 forecast and NYMEX futures prices. The levelized price of coal is based on EIA AEO 2007 forecast for coal prices for PRB coal.

Transmission

We consider a transmission line from southern Wyoming to southern California via southern Nevada as a representative transmission line for estimating transmission costs for options located in Wyoming. The cost estimate for this line is based on the estimate developed in the Frontier Line study (WRTEP, 2007a). Note that the straight line distance is increased by 30% to account for line routing issues in estimating the cost of the line. The transmission line from southern Wyoming to load centers in Arizona via southern Nevada will have a similar total straight line distance and costs; hence we do not analyze these costs separately. We analyze the sensitivity of our results to assumptions regarding total transmission costs. For the option located near the load center (CCGT plant), we assume a transmission distance of 100 miles and the transmission costs are for a 3,000 MW HVAC line.

CO2 Related Costs

Emission Allowance Prices

For our base case, we estimated the levelized price emission (CO_2) allowances during 2015-45 based on a number of recent studies, including those conducted by EIA on various climate bills proposed by the US Congress which estimate the cost of stabilizing the CO2 concentration in the 450 to 550 ppm range. We assume a levelized CO_2, price of \$40/ton CO_2 during the 2015-45 in our base case analysis and analyze the sensitivity of our results to a wide range of carbon emission allowance prices.

Cost of Carbon Transport and Geologic Storage and EOR Revenues

The fixed and variable costs of carbon capture are already included in the cost of generation. In addition to carbon capture costs, additional costs are incurred for carbon transport and geologic storage. Given the enhanced oil recovery (EOR) opportunities in the West, the CO_2 captured can be used for EOR. The revenues from EOR will more than offset the cost of CO_2 transport and storage. For our base case, we assume that the cost of carbon transport and storage (which is about $7/MWh) will be offset by the EOR revenues. We analyze the sensitivity of our results to this assumption.

Costs Related to Variable Generation

Wind Integration Costs

Wind integration costs, which primarily include costs associated with integrating variable wind generation in the power system, depend primarily on the characteristics of wind generation (e.g., the level of penetration, variance, predictability, and correlation with the system load), load, and generation resources in the system. Given the RPS requirements of the states in the West and current trends in wind capacity additions, a wind penetration level of 10% or more is a reasonable assumption for the period considered in this analysis (2015-45). At this penetration level, most studies show integration costs in the range of $3 to $5/MWh (NREL, 2006). We assume an integration cost of $3/MWh for our Base Case and test the sensitivity of our results to alternative assumptions about integration costs.

Resource Adequacy (Capacity) Cost

Resource adequacy cost (which is added to the cost of the stand-alone wind generation option) is based on the cost of the additional capacity required to make the capacity contributions per unit of energy produced by wind equivalent to other baseload options. The cost of additional capacity is based on the capital cost of a CT. Additional capacity requirement is the difference in the capacity contributions by a baseload plant that produces the same amount of electricity as the wind plant and the capacity contributions by the wind plant.

Financing Costs

We assume utility financing for all generation options considered in our analysis (see Table 4).[27] The financing assumptions are based on those assumed in the Frontier Line Study (WRTEP, 2007b) and were reviewed by the Analysis Team and Steering Committee. Because we estimate levelized costs in real (2007) dollars, we use real debt

[27] If we assume merchant financing, the fixed cost per unit of electricity produced will be higher (by about 10% to 15%) for all the generation options compared to a case where we assume utility financing. The effect of assuming merchant financing instead of utility financing is very similar to assuming higher capital cost for all generation options. We analyze the effect of higher capital costs in one of our sensitivity scenarios.

and equity rates to estimate levelized costs.[28] Levelized costs are estimated using accelerated depreciation schedules used by utilities.[29]

Table 4. Financing Assumptions

Utility Financing	
Debt Rate (Nominal)	6.0%
Return on Equity (Nominal)	10.7%
Inflation Rate	2%
Debt Rate (Real)	4.0%
Return on Equity (Real)	8.7%
Debt %	45%
Equity %	55%
Weighted Average Cost of Capital (Real)	6.6%
After Tax Weighted Average Cost of Capital (Real)	6.0%
Discount Rate	6.0%

[28] TALC in nominal dollars (estimated using nominal debt and equity rates) will be higher than TALC is real dollars. Even if TALC is estimated in nominal dollars, the relative competitiveness of ACWH and competing options, which is our primary interest, will be very similar to what is found by estimating TALC in real dollars.

[29] We do not consider the production tax credit given to wind technologies as the continuation of this policy in the future is uncertain. We assume a federal tax rate of 35%. For generation options in Wyoming, we do not assume any state taxes as Wyoming does not levy state taxes while for options located near load centers, we assume a state tax rate of 5%.

6. Results

In this section, we first compare several different ACWH configurations in order to establish a preferred ACWH option. We then analyze the net benefits of a hybrid configuration for the preferred ACWH option by comparing it with a benchmark advanced coal-wind facility which is operated in a stand-alone (i.e., non-hybrid) manner. Finally, we compare the preferred ACWH option with other competing hybrid and non-hybrid options.

6.1 Comparing Among ACWH Options

Figure 5 shows the ACWH configurations that were analyzed.

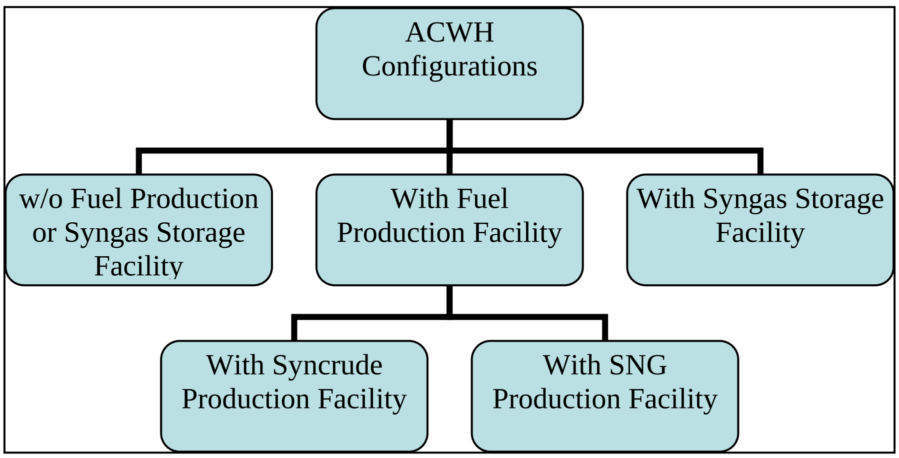

Figure 5. ACWH Configurations

We analyze two ACWH options with a fuel production facility (i.e., a syncrude production facility and a synthetic natural gas (SNG) production facility) and an ACWH configuration with a syngas storage facility. We find that adding a fuel production or a syngas storage facility improves the utilization of the capital intensive G+CC+CCS plant in the ACWH, which lowers the fixed cost per unit of electricity produced. This benefit outweighs the extra cost of fuel production or the cost of syngas storage. Hence the TALC of the ACWH with a fuel production or a syngas storage facility is lower than that of the ACWH without a fuel production or a syngas storage facility (see Table 5). We also find that the TALC of ACWH options with a fuel production or a syngas storage facility is comparable.

Table 5. Total Adjusted Levelized Cost of ACWH Options

	ACWH Configurations			
	Without Fuel Production or Syngas Storage Facility	with Syncrude Production Facility	with SNG Production Facility	with Syngas Storage Facility
Total Adjusted Levelized Cost ($/MWh)	77.5	72.9	72.8	72.8
Levelized Cost of Fuel Production	NA	$60/bbl	$7.25/MMBtu	NA
Total Production in a Year		6.29 Million bbl	44 Million MMBtu	

The additional costs of fuel production or syngas storage that are allocated to the ACWH options is the only factor that drives differences in total adjusted levelized costs. As Table 6 shows, these additional costs are comparable across the various options.

Table 6. Extra Costs of Fuel Production or Syngas Storage

ACWH	Additional Cost ($ Million)	Averaged Over Total Generation ($/MWh)
Syncrude	424	1.4
Synthetic Natural Gas (SNG)	358	1.3
Syngas Storage	380	1.3

Note: See Appendix D for the estimation of these costs

Hence, the choice of a particular ACWH option will depend on factors other than their TALC. One important factor is the cost of fuel production for ACWH configurations with a fuel production facility (see Table 5). For our analysis, we have assumed a levelized natural gas price of $7.35/MMBtu during the 2015-45 period, which is slightly higher than our estimate of the levelized cost of SNG production ($7.25/MMBtu). Although we have not estimated the levelized oil price during 2015-45, based on the current trend in oil prices, the levelized oil price during 2015-45 is likely to be substantially higher than $60/bbl, which is our estimate of the cost of syncrude production. Thus, the ACWH with a syncrude production facility is likely to be more profitable than the ACWH with a SNG production facility. At the same time, ACWH with a syncrude production facility may not always be preferred because the ACWH with syngas storage facility does not involve the risks associated with fuel production. Finally, the choice of an ACWH option is unlikely to be determined by its emission footprint because it does not vary significantly across ACWH options considered in this analysis (see Section 7). We select the ACWH with a syncrude production facility as the preferred ACWH options for the following reasons.

- The fuel production from the ACWH with a syncrude production facility is likely to be more profitable that that from the ACWH with a SNG production facility.
- The cost of electricity generation for an ACWH project with a syncrude production facility is slightly higher than other options. Thus, if the ACWH project with a syncrude facility is competitive compared to other competing generation technologies, then our results will also be applicable for other ACWH configurations considered in this analysis that had slightly lower TALC.

If projections of fuel prices change substantially and expected fuel prices during 2015-45 are below the cost of syncrude or SNG production, then the ACWH with a syngas storage facility will be the preferred option. The results of comparing the levelized cost of electricity of the currently preferred ACWH option (i.e., ACWH with syncrude production) with other competing non-ACWH options will be almost identical if the preferred ACWH option is an ACWH with a syngas storage facility. This is because the levelized costs of electricity among ACWH options with a fuel (syncrude or SNG) production or a syngas storage facility are comparable.

Before comparing the ACWH option with a syncrude production facility with other competing options, we analyze the net benefits of the hybrid configuration for this preferred ACWH option. We refer to the ACWH with a syncrude production facility as the ACWH option in the rest of this report.

6.2 Analysis of the Net Benefits of the ACWH Configuration

One of our primary objectives in this study was to assess the net benefits of configuring wind and advanced coal in a hybrid configuration instead of operating them in a stand-alone (non-hybrid) manner. Comparing the TALC of the ACWH facility with the TALC of stand-alone wind and advanced coal projects, individually, is informative (see Section 6.3.2), but does not directly address the specific benefits that come from joint optimization of wind and advanced coal operation in a hybrid configuration.[30]

To analyze those benefits directly requires a comparison of the ACWH facility with a benchmark facility that includes both wind and advanced coal, but with each operated in a stand-alone (non-hybrid) manner. We therefore consider a benchmark coal-wind facility that has the following characteristics. First, unlike in the case of the ACWH, this

[30] For example, even if we find that the TALC of the ACWH is lower than that of the stand-alone wind generation option, we can not immediately determine whether that lower TALC is the result of the hybridization (i.e., joint optimization of operations) or whether it is simply due to the fact that coal generation is less expensive than wind. Comparing the TALC of the ACWH to that of a stand-alone advanced coal plant would help inform that decision, but still represents an indirect way of evaluating the merits of hybridization.

coal-wind facility requires sufficient transmission capacity to accommodate the aggregated peak of wind and coal generation.[31] Under this configuration, the advanced coal plant (IGCC+CCS) will operate in stand-alone mode, and will therefore not back down to accommodate wind generation. Second, to enable a fair comparison with the ACWH, this hypothetical facility must have the same ratio of coal to wind generation as that in the ACWH.[32]

Because it operates wind and coal in a stand-alone fashion, this benchmark facility results in lower utilization of transmission lines compared to the ACWH and incurs integration and resource adequacy costs for the wind generation. At the same time, unlike the ACWH, it does not incur costs associated with lower utilization of the power generation units and the extra costs of fuel production or syngas storage.

We compare the total adjusted levelized costs of the ACWH facility and the benchmark coal-wind facility to estimate the net benefit of the ACWH configuration. Using base-case assumptions, we find that the TALC of the benchmark facility is $75.4/MWh vs $72.9/MWh for the ACWH. The TALC of the ACWH is about $2.5/MWh (~3.5%) lower than a similar coal-wind facility that operates in a stand-alone manner. This result suggests that the benefits are somewhat greater than the costs of the hybrid configuration.

Table 7 provides a breakdown of this $2.5/MWh advantage by highlighting more specifically the economic tradeoffs between the ACWH facility and the benchmark advanced coal-wind facility that does not operate in a hybrid manner.

Table 7. Benefits of the ACWH Relative to a Benchmark Coal-Wind Facility

	$/MWh	**$Million/ Year**	**$ Million Total Over the Life of the Project**
Benefits			
Improved Utilization of Transmission	3.1	78	$1,073
Avoided Wind Integration and Resource Adequacy Costs	1.8	46	$627
Improved Utilization of the Gasifiers	0.5	13	$185
Total	*5.5*	*137*	*$1,886*
Costs			
Higher Fixed Costs due to Lower Utilization of the Power Generation Unit	1.5	38	$530
Higher Fixed Costs due to Lower Utilization of the Fuel Production Units	1.4	36	$494
Higher Variable Costs due to Lower Heat Rate	0.0	0	$2
Total	*3.0*	*74*	*$1,025*
Net Benefit (Benefits-Costs)	**2.50**	**62.5**	**$860**

.

[31] To model the effect of wind capacity overbuild, we also consider a scenario in which transmission capacity is equal to the peak coal generation plus 80% of the peak wind generation.

[32] Equivalence in the relative contributions of wind and coal is necessary to uniquely determine the value of hybridization; otherwise, cost differences between the two facilities may simply be the result of different resource mixes.

As Table 7 shows, the ability of the ACWH to improve transmission utilization is of greatest incremental economic benefit. Avoidance of wind integration and resource adequacy costs provides a moderate benefit of the ACWH, while improved gasifier utilization offers a modest advantage. The largest additional costs associated with the ACWH come from lower utilization of the power generation units and fuel production facility, while the heat rate penalty is found to be very small. Again, on net, it appears as if the hybrid operation allowed by the ACWH has merit compared to the benchmark coal-wind facility operated on a stand-alone basis using base case assumptions. We also analyzed the sensitivity of these results to changes in several key assumptions (see Table 8).

Table 8. Sensitivity Analysis of ACWH option vs. Benchmark Coal/Wind Facility

	Net-Benefit ($/MWh)	Net-Benefit Annual ($Million)	Net-Benefit NPV over the life of the project ($Million)
Base Case	2.5	62	860
Sensitivty to Resource Adequacy and Integration Costs			
20% Higher Resource Adequacy and Integration Costs than the Base Case	2.9	72	985
20% Lower Resource Adequacy and Integration Costs than the Base Case	2.1	53	735
Sensitivity to Tansmission Costs			
Transmission Costs 27% Higher than the Base Case (HVAC Transmission)	3.3	83	1149
Transmission Costs 19% Lower than the Base Case (HVDC Only Transmission)	1.9	48	657
Sensitivity to Capital Costs			
ACWH Capital Cost 20% Higher than the Base Case	2.3	58	792
ACWH Capital Cost 20% Lower than the Base Case	2.7	67	928

The results of this analysis are as one would expect. The net benefit of ACWH configuration increases as resource adequacy and integration costs increase because the ACWH configuration avoids these costs. The net benefit also increases with transmission costs because a key benefit of the ACWH is to increase transmission utilization. Finally, the net benefit decreases with comparable increases in the capital cost of ACWH and benchmark advance coal-wind facility. This occurs because the cost associated with backing down of the power generation units in the ACWH increases with its capital cost.

Interestingly, the net benefit of the ACWH configuration, compared to the benchmark coal-wind facility, is relatively insensitive to these variations in input parameters. In each sensitivity case, the ACWH facility maintains a modest advantage in levelized costs relative to the coal-wind benchmark facility that operates in stand-alone mode.

6.3 Comparison with Competing Options

We next compare the ACWH configuration with a syncrude production facility with other hybrid and non-hybrid options. For the remainder of this report, we refer to ACWH configuration with a syncrude production facility as the ACWH configuration.

6.3.1 Comparison with other Hybrid Options

Wind generation can be combined with other generation technologies to improve transmission utilization and avoid wind integration and resource adequacy costs. The generation technology used in a hybrid configuration with wind needs to have the ability to change its output rapidly to accommodate the variations in wind generation. We compared the ACWH option with two other hybrid options: a CCGT-Wind hybrid and a CT-Wind hybrid. We find that the TALC of a CCGT-Wind hybrid is lower than that from a CT-Wind hybrid under most scenarios of natural gas and emission allowance prices. Thus, we focused primarily on comparisons between a CCGT-Wind hybrid and the ACWH option and examined the levelized costs of these hybrid options at varying natural gas and emission allowances prices in order to understand the circumstances under which the ACWH option is preferred. For an emission allowance price of $40/ton (which is our base case assumption), the ACWH option is cheaper than a CCGT-Wind hybrid option if the natural gas price is above $3.7/MMBtu (see Figure 6). We assumed a levelized natural gas price of $7.3/MMBtu in our base case for natural gas delivered in the Pacific Region. At this price, the ACWH is more economical than CCGT-Wind Hybrid.[33] However, natural gas prices in Wyoming have been lower than those in California and other parts of the Pacific Region. As seen in Figure 7, the difference in prices increased drastically during 2007, however in the last few months, this difference has narrowed below $0.50/MMbtu. Given the trend in natural gas prices in Wyoming, we believe that the ACWH option is likely to be cheaper than a CCGT-wind hybrid option in Wyoming.

[33] A CCGT-wind hybrid in Wyoming is economical if the price difference between natural gas prices in Wyoming and Southern California justifies the transmission costs associated with a CCGT plant in Wyoming. If this price differential is small enough, a load center CCGT plant which cycles with wind generation in Wyoming will be a cheaper option than a CCGT-wind hybrid option.

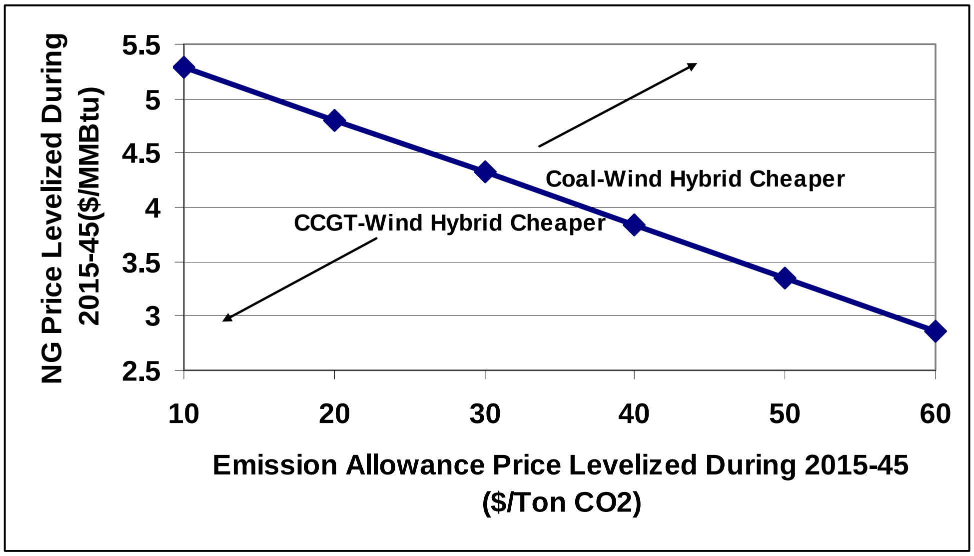

Figure 6. Comparison of ACWH and CCGT-Wind Hybrid

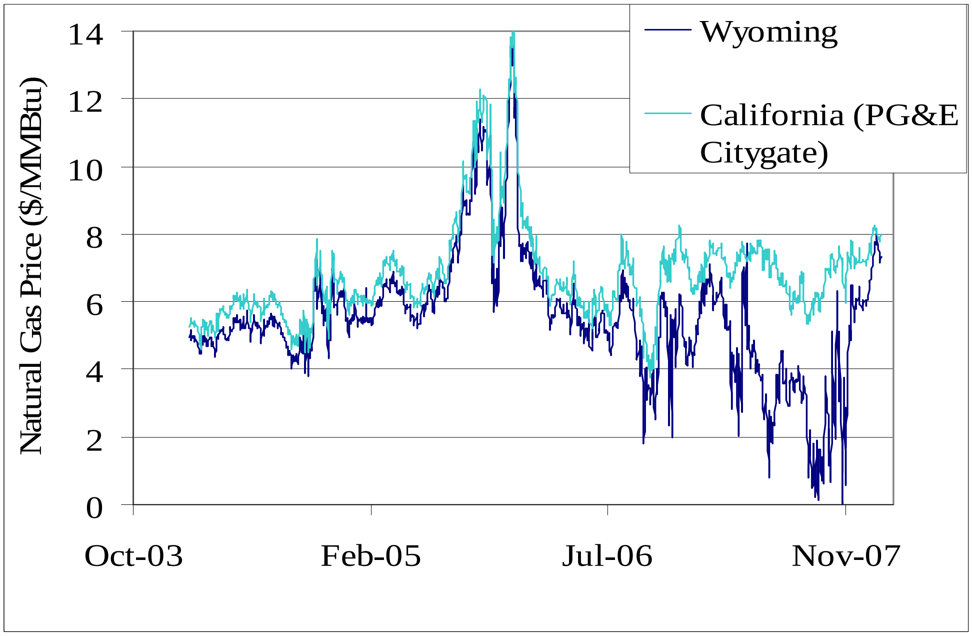

Figure 7. Natural Gas Prices in California and Wyoming
Source: Velocity Suite, Global Energy Data

6.3.2 Comparison with Non-hybrid Competing Options

We compare the TALC of the ACWH option with other competing options assuming the goal is to meet the base-load requirement.[34] We first present the results using base case assumptions (see Table 9) and then analyze the sensitivity of our results by changing key input assumptions.

Table 9 shows the key components of the TALC including generation, transmission, emission allowance, resource adequacy, and integration costs. For the ACWH option, we show these costs separately for the G+CC+CCS coal plant and the wind plant. The cost for the ACWH has the lowest levelized costs and is a weighted average (by percentage generation) of the cost of the G+CC+CCS and wind plant. The ACWH has a clear advantage over a PC plant located in Wyoming and a CCGT plant located near the load center. Electricity from a PC plant is more expensive than that from an ACWH primarily because the generation from a PC plant incurs substantial emission allowance costs ($36/MWh).

Table 9. Comparison with Competing Options: Base Case Results

	Advanced Coal in Wyoming	Wind in Wyoming	ACWH with Syncrude Production in Wyoming		CCGT Load Center	PC in Wyoming
	IGCC+CCS	Wind	G+CC+CCS	Wind		
Capacity (MW)	3000	3600	3000	1500	3000	3000
Transmission Capacity (MW)	3000	3000	3000		3000	3000
Total Levelized Cost ($/MWh)	**75**	**78**	**73**		**83**	**87**
Variable Generation Cost ($/MWh)	15	6	15	6	54	10
Fixed Generation Cost ($/MWh)	41	41	42	41	12	25
Transmission Cost ($/MWh)	17	23	16	15	3	17
Emission Allowance Cost ($/MWh)	2	0	2	0	15	36
Extra Cost of Fuel Production ($/MWh)			1.4			
Resource Adequacy Cost ($/MWh)	0	4.3	0	0	0	0
Integration Cost ($/MWh)	0	3	0	0	0	0
Generation Fraction	100%	100%	75%	25%	100%	100%

The levelized costs of electricity for the ACWH option has slightly lower costs than a stand-alone IGCC+CCS coal plant and a stand-alone wind plant. Our analysis does not take into account the difference in the level of risk associated with the cost of these options (for example, wind plants are a more proven technology than advance coal and hence their cost estimates are more reliable). In this context, we argue that the advantages of the ACWH over wind are not as significant given the small difference in the cost of

[34] Hence we estimate TALC assuming that the resource is operating at its maximum capacity factor.

these options. The CCGT plant has higher levelized costs primarily because of its high variable generation costs (driven by our assumed gas price of $7.3/MMBtu) and emission allowance costs.

6.3.3 Sensitivity Analysis

In this section, we analyze the competitiveness of the ACWH option with other options under different assumptions for key input parameters (e.g., natural gas and emission allowance prices). We calculated "break-even" values for key input parameters which provide insight on the circumstances in which the ACWH will be a preferred option.

Competitiveness with a Load Center CCGT Plant

The competitiveness of the ACWH compared to a CCGT plant located near the load center primarily depends on natural gas and emission allowance prices. The advantage of the ACWH over the CCGT plant increases with higher natural gas and emission allowance prices (see Figure 8).

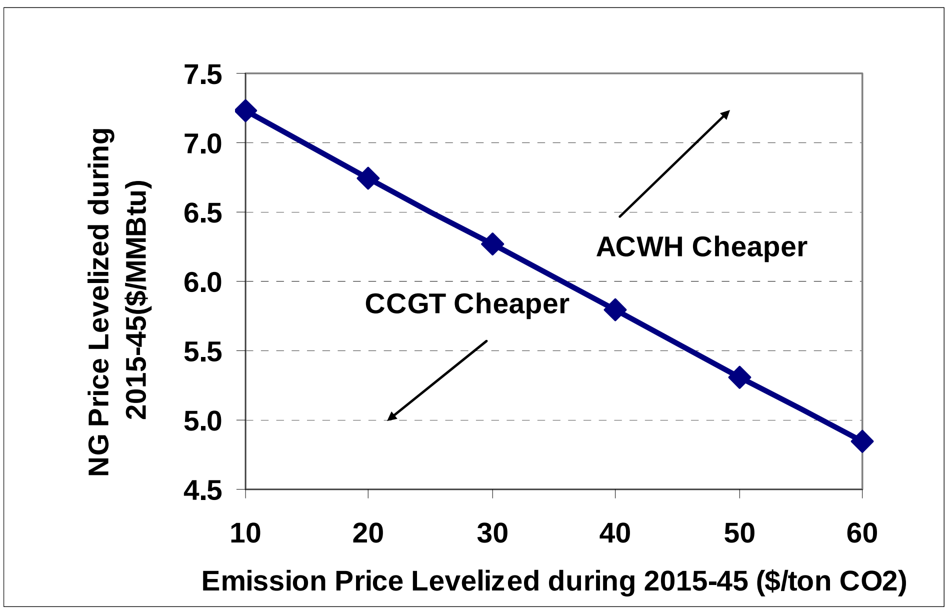

Figure 8. Competitiveness of the ACHW with a Load Center CCGT

Note: Levelized prices are in real 2007$. A levelized price of $7.3/MMBtu corresponds to a price of $6.50/MMBtu in 2015. The levelized price during 2015-45 is higher than the price in 2015 because prices are assumed to increase in real terms over this period.

For example, if emission allowance prices are $40/ton, then the ACWH option will be more economical than the CCGT plant even if the levelized natural gas price during 2015-45 is as low as $5.7/MMBtu. Conversely, at our assumed base case levelized natural gas price of $7.30/MMBtu, the ACWH option is cheaper than the CCGT option even if the levelized price of CO2 emission allowances is as low as $10/ton. Emission allowance prices are likely to be higher than this level under most moderate to stringent climate regulation regimes.

Sensitivity to Coal Prices

Figure 9 is similar to Figure 8 except the natural gas prices above which the ACWH is cheaper than the CCGT are estimated at different coal prices.

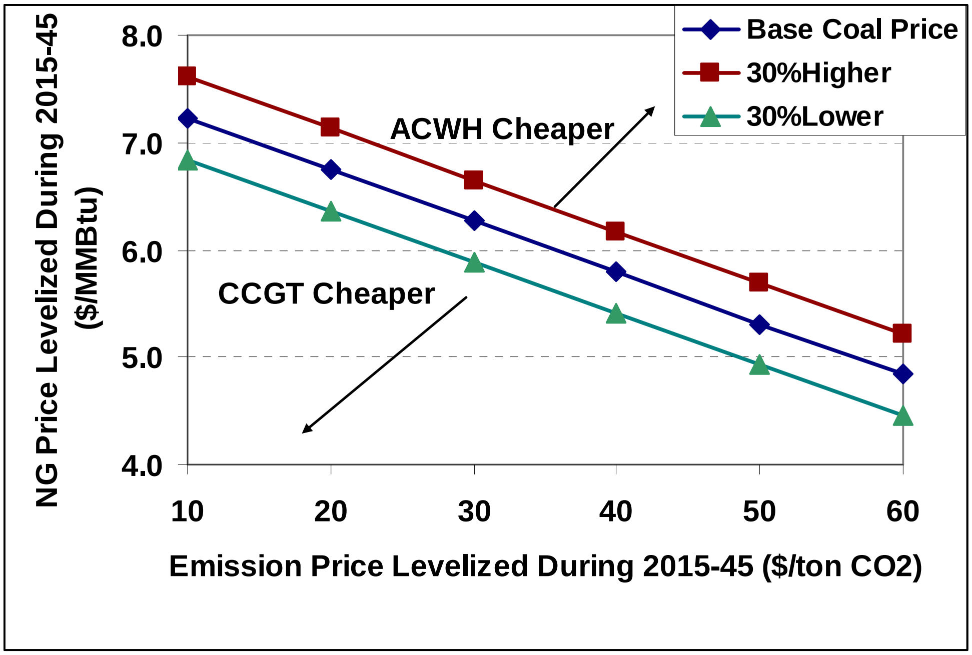

Figure 9. Sensitivity to Coal Prices

As seen in Figure 9, our results are not very sensitive to coal prices. For example, if the coal price is 30% higher than that assumed in our Base Case, the cut off price for natural gas above which the ACWH option is cheaper than the CCGT increases from $5.70/MMBtu to $6.20/MMBtu (at an emission allowance price of $40/ton).

Competitiveness with PC Generation

The competitiveness of the ACWH with a PC plant located in Wyoming primarily depends on emission allowance prices. Figure 10 shows the TALC for the PC plant and the ACWH at different emission allowance prices. The ACWH option is more economical than the PC plant if the levelized emission allowance price during 2015-45 is above $22/ton of CO_2. For our Base Case assumption of $40/ton of CO_2, the ACWH is substantially cheaper than the PC plant.

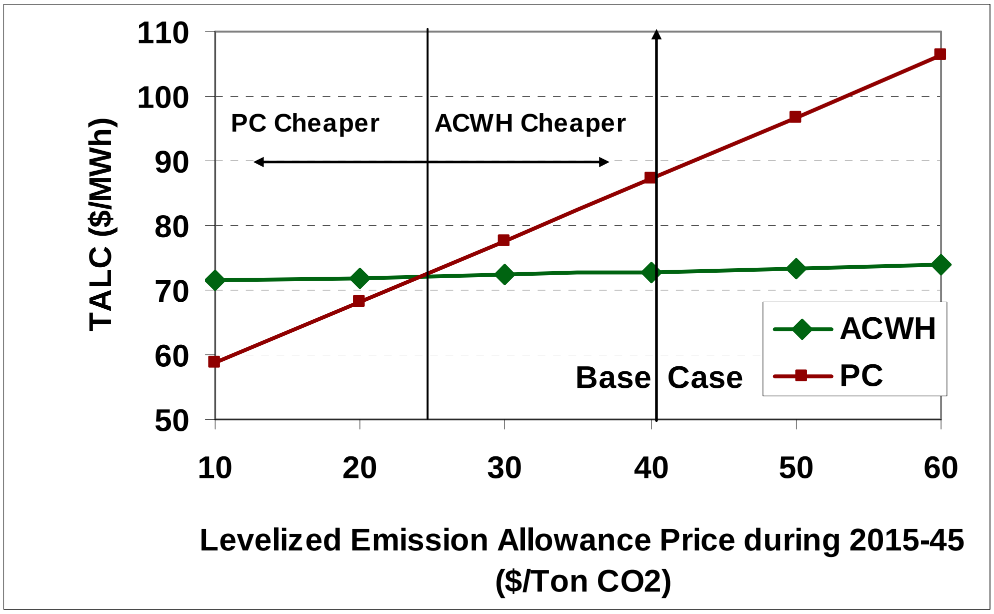

Figure 10. Comparison of PC and Hybrid

Competitiveness with Stand-Alone Wind Generation

The competitiveness of the ACWH option with a stand-alone wind generation option located in Wyoming primarily depends on the assumption of wind capacity factor, integration costs, and resource adequacy costs. The effect of wind capacity factor on the TALC of a stand-alone wind project vs. the ACWH is shown in Figure 11.

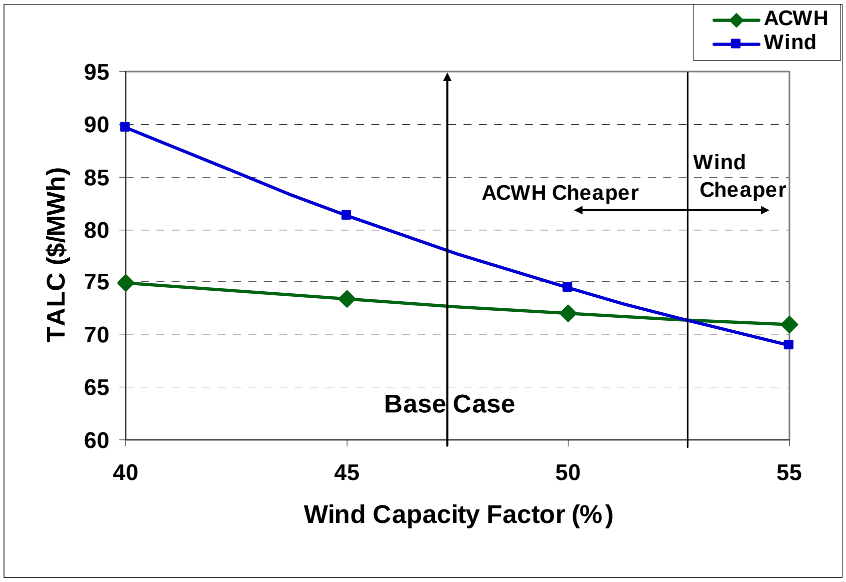

Figure 11. Wind Capacity Factor and Total Adjusted Levelized Cost of Electricity

The TALC of stand-alone wind generation is very sensitive to the assumption of wind capacity factor because it influences the utilization of the wind plant as well as the utilization of transmission lines. The benefits of the ACWH over a stand-alone wind generation option will be higher if the wind capacity factor is lower. For example, if the actual wind capacity factor is 40% instead of 47% (which is our base case assumption), the TALC of the ACWH will be $15/MWh lower than that of the stand-alone wind generation whereas this difference for our Base Case is $4/MWh.

Effect of Wind Integration and Resource Adequacy Costs

Figure 12 shows the effect of the assumptions of wind integration and resource adequacy costs on the TALC of wind generation.

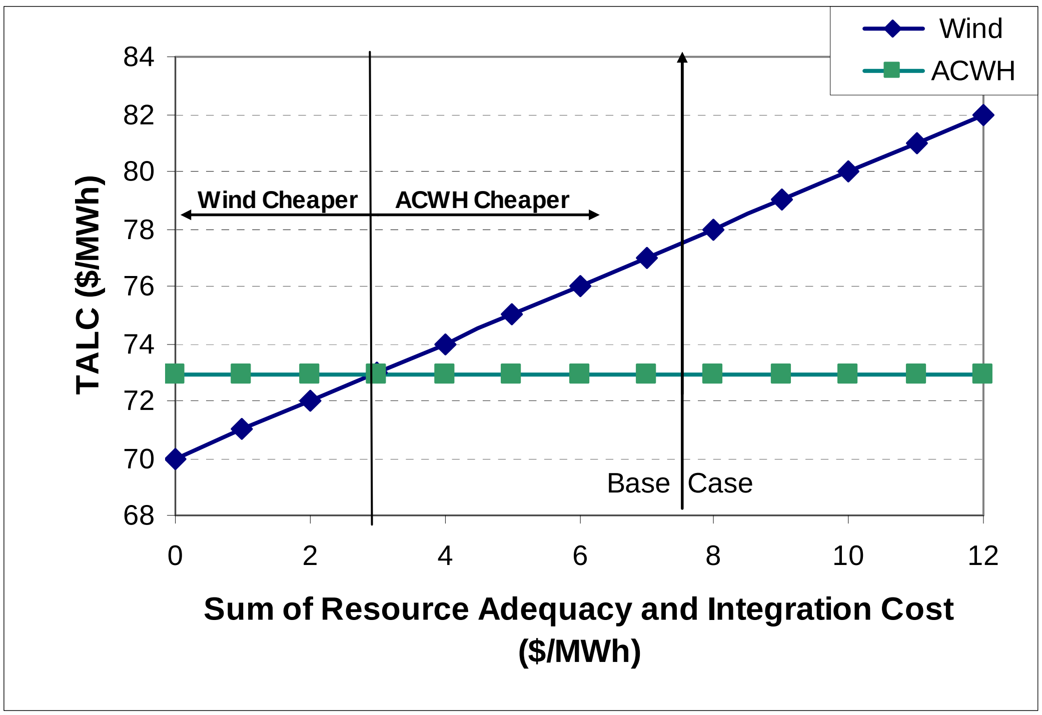

Figure 12. Effect of Wind Integration and Resource Adequacy Costs

For the stand-alone wind generation option, we assume an integration cost of $3/MWh and a resource adequacy cost of $4.3/MWh in the base case. The benefits of the ACWH option increase with higher wind integration and resource adequacy costs. This is because one of the key benefits of the ACWH option is avoiding wind integration and resource adequacy costs.

Competitiveness with a Stand- Alone IGCC+CCS Coal Plant

The levelized cost of electricity from the hybrid and the stand alone IGCC+CCS plant is not affected significantly, if at all, by the uncertainties in assumptions regarding natural gas and emission allowances prices. Factors like coal prices and EOR revenues affect the relative competitiveness of the ACWH compared to a stand-alone IGCC+CCS plant only to a limited extent since they affect both options in a similar fashion. Our results suggest that the levelized costs of generation from the ACWH are likely to be lower compared to a stand alone IGCC+CCS plant under most circumstances.

Effect of EOR Revenues

For the Base Case scenario, we assume that the revenues from EOR will offset the cost of carbon transport and storage. It is possible that EOR revenues are substantially higher and are a source of net revenue to the power producer. Assuming higher EOR revenues improves the competitiveness of the stand-alone coal and the ACWH option substantially compared to a stand-alone wind option and a CCGT option (Figure 13).

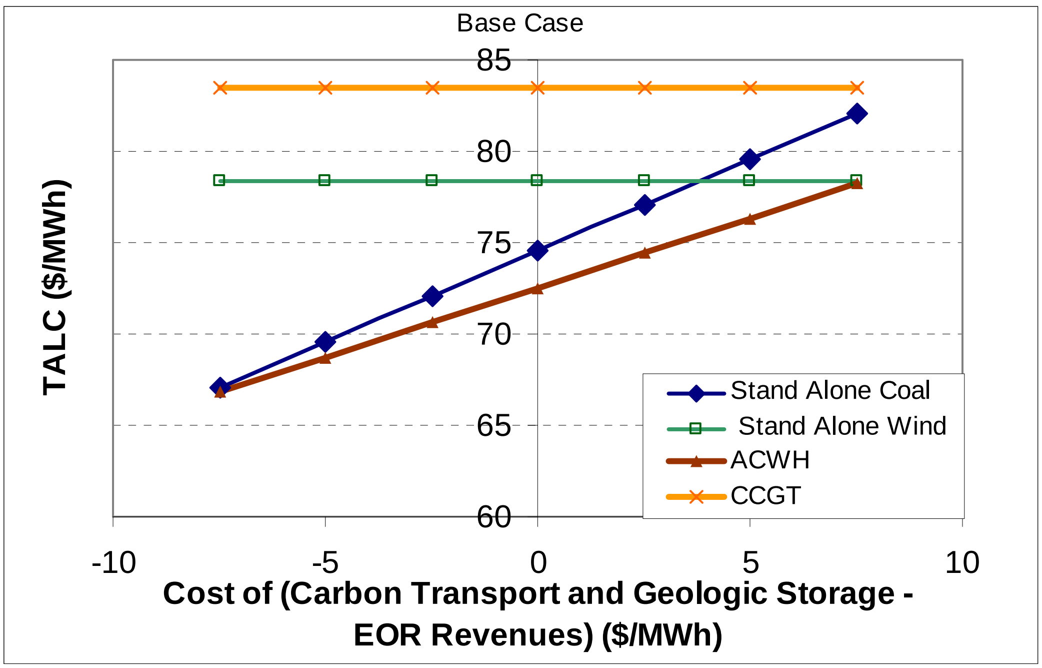

Figure 13. Effect of EOR Revenues on Levelized Cost of Electricity

Sensitivity to Capital Costs

Figure 14 shows the effect of the changes in the capital cost of the ACWH and competing options on their TALC. The TALC of a CCGT plant is less sensitive to changes in capital costs compared to a stand-alone wind project and an ACWH project. The sensitivity of the TALC to the assumptions about capital costs is comparable between stand-alone wind and the ACWH option even though the capital intensity of wind generation is about 60% of the ACWH. This is because the capacity factor of wind generation is about half that of the ACWH, which effectively increases its capital intensity per unit of electricity produced. If the capital cost of all technologies is 20% higher than that assumed in the base case, the advantage of the ACWH option over the CCGT option erodes away. This is one of the important findings related to the competitiveness of the ACWH option given the significant uncertainties in the capital costs of an ACWH project.

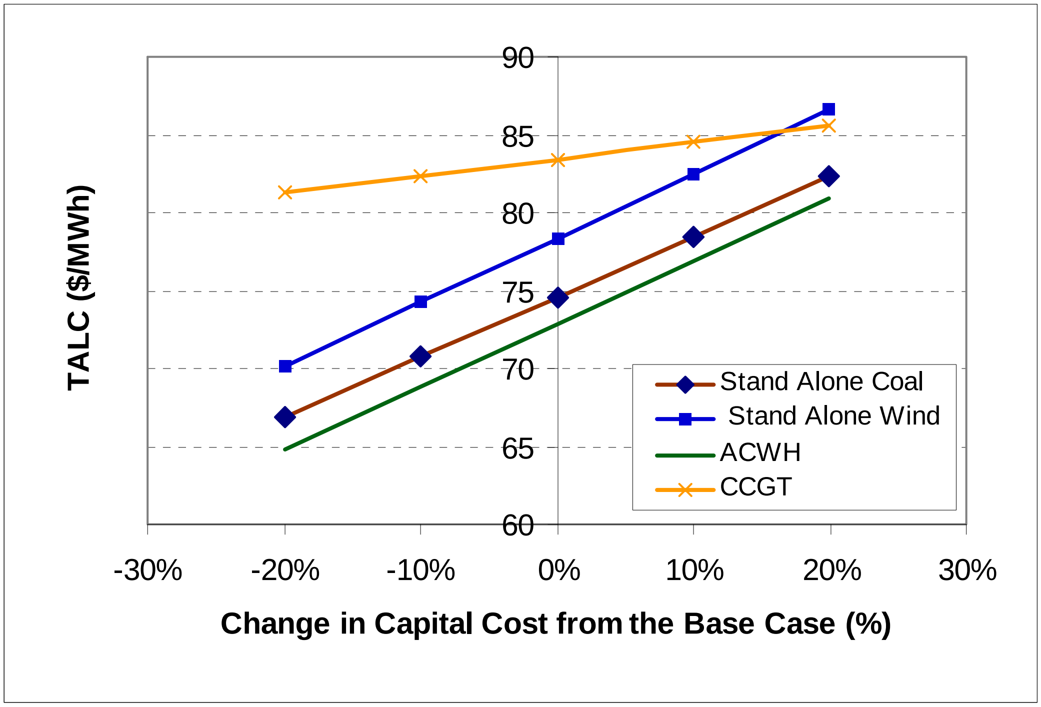

Figure 14. Sensitivity to the Assumptions about Capital Costs

Alternatively, if the capital costs of each technology are 20% lower, the cost advantages of an ACWH project increases compared to a CCGT plant.

7. Emission Footprint of ACWH and Competing Options

In this section, we compare the CO_2 footprint and the footprint of several criteria pollutants (i.e., SO_X, NO_X, and Mercury) of the ACWH and competing options.

7.1 Carbon Footprint

Figure 15 shows CO2 emissions per year from the ACWH and competing options. Each ACWH option is equipped with carbon capture equipment, which captures over 90% of the CO_2 produced.[35] ACWH options and the stand-alone IGCC+CCS plant have substantially lower CO2 emissions than pulverized coal and CCGT plants. For ACWH configurations with a fuel production facility, we estimate CO_2 emissions from electricity generation and fuel production (shown separately in the stacked bars in Figure 15).

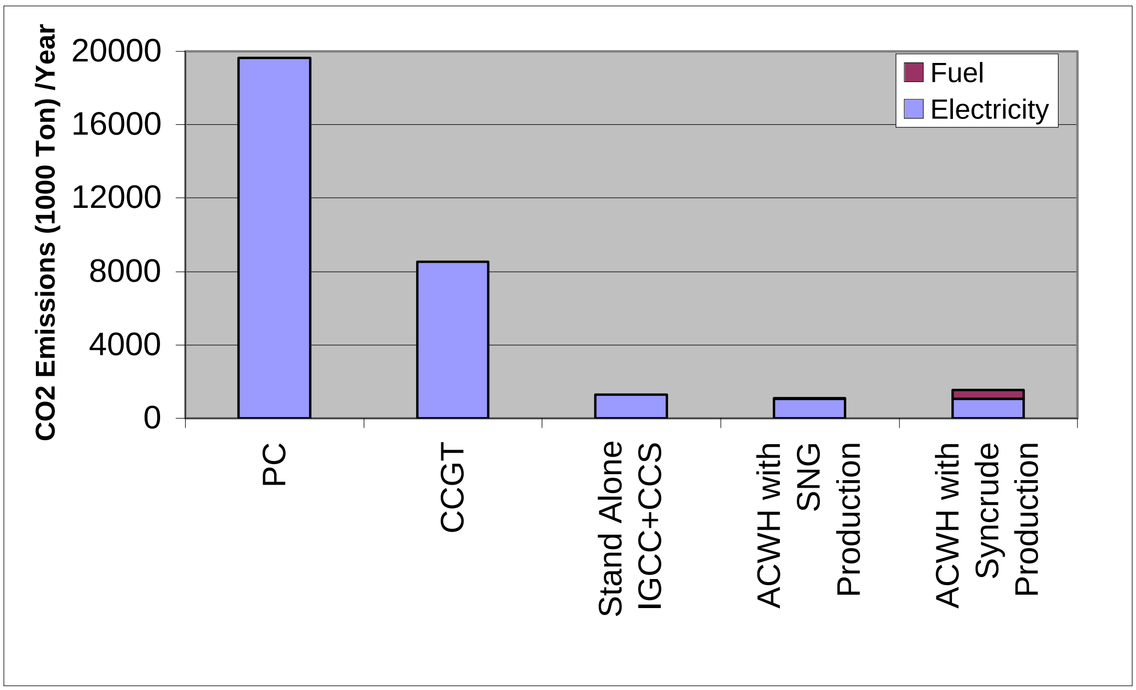

Figure 15. CO2 Emissions from ACWH and Competing Options

Note: Hybrid and competing options have a capacity of 3,000 MW

The emissions associated with SNG production are not large enough to be seen in Figure 15.

[35] The CO_2 emissions from electricity generation include the emissions associated with the electricity used in the electricity generation, carbon capture, and sequestration process.

Comparison with the Footprint of Conventional Fuel Production

We compare the emission footprint of syncrude and SNG production in the ACWH options with crude oil and natural gas production respectively to evaluate whether fuel production in the ACWH options has a greater emission footprint than that of conventional fuel production.

SNG Production

We estimate that the CO_2 emissions from SNG production in the ACWH facility are about 0.6 grams of CO_2 equivalent per mega joule (MJ). NETL and DOE (2006) show that the emissions from the production and supply of domestically produced natural gas are about 1 gram of CO_2 equivalent per MJ and those for imported LNG are about 11 grams of CO2 equivalent per MJ.[36] SNG is likely to replace the marginal supply of natural gas, which in the US is imported LNG that has substantially higher emissions associated with its production and supply.

Syncrude Production

We estimate that the CO_2 emissions from syncrude production in the ACWH facility are 139 lb/bbl. Table 10 shows the CO_2 emissions from the production and refining of regular crude oil into low sulphur diesel fuel and naphtha. We can not directly compare the CO_2 emitted from the production of diesel and syncrude, because diesel is a more refined product. In terms of the level of refining, syncrude is similar to naphtha. CO_2 emissions from the production of naphtha (134.5 lb/bbl) are similar to those from the production of syncrude (139lb/bbl).

Table 10. CO2 Emissions from Production and Refining Crude Oil into Low-Sulfur Diesel Fuel and Naphtha

	Crude Oil Production/ Transportation	**Refining**	**Refining – Non-Combustion Emissions**	**Total**
CO2 Emissions (lbs CO2/barrel diesel)	44.5	131.8	13.9	190.2
CO2 Emissions (lbs CO2/barrel naphtha)	49.0	78.8	8.7	134.5

Source: NETL, 2007b

[36] The primary reason for higher emissions from LNG production and supply is the emissions associated with liquefaction and re-gasification of natural gas which consumes considerable amount of energy.

7.2 Emission Footprint of Criteria Pollutants

We focus on comparing the SO_X, NO_X, and mercury emissions associated with electricity generation from the G+CC+CCS coal plant in the ACWH facility to other competing options.[37]

Compared to a conventional PC plant, the G+CC+CCS coal plant in the ACWH facility has substantially lower SO_X and NO_X emissions: 53 thousand tons/year of SO_X (only 0.4% of those from a PC plant) and 3700 thousand tons/year of NO_X (about 50% of those from a PC plant). The G+CC+CCS plant also has substantially lower mercury emissions compared to a PC plant.

However, compared to a CCGT plant, NO_X emissions from the G+CC+CCS coal plant in the ACWH facility are about five times higher. SO_X, NO_X, and mercury emissions from the IGCC+CCS plant are very similar to those from the G+CC+CCS plant in the ACWH facility.

[37] The SOX, NOX, and mercury emissions associated with fuel production are not significant.

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Appendix A. Costs and Benefits of the ACWH

In this appendix, we provide additional information on the costs and benefits of ACWH options which are summarized in Section 2.

Benefits of the ACWH configuration

1. Improved Transmission Utilization

In Comparison with a Stand-Alone Wind Project Option

Given the capital intensity of long distance transmission lines, there is significant economic value in improving utilization factors. All else being equal, we would expect the transmission capacity utilization factor to be higher with a hybrid project configuration compared to a stand-alone wind project, given the differences in capacity factors among these two options.

In Comparison to a Stand- Alone Coal Generation Option (IGCC+CCS coal plant)

In a stand-alone coal generation option where only the power generated from the coal plant is transmitted over the transmission lines, an outage (forced or planned) of the IGCC+CCS plant lowers the utilization of the transmission lines. However, in the ACWH configuration, the utilization of transmission is less affected by an outage because some of the power generation units in the ACWH configuration are backed down to accommodate wind generation. If an outage (forced or planned) occurs in one of the power generation units, the units which are backed down to accommodate wind generation can be ramped up to make up for most of the loss in power generation due to the outage. This option is not available in a stand-alone coal generation plant because none of its units are backed down below full rated capacity during normal operation. Table A-1 shows the probability of different sizes of outages and the uncovered generation (i.e., the amount of generation that is not available even after the backed down power generation units are ramped up) for the stand alone-coal and ACWH options. The loss in transmission utilization due to outages of the G+CC+CCS plant is 5% for the ACWH configuration compared to 15% for the stand-alone coal generation (IGCC+CCS) option.

Table A-1. Improved Transmission Utilization with the Hybrid Configuration

		IGCC+CCS	ACWH		
Probability of the Outage	Size of the Outage	Loss in Transmission Utilization	Backed Down Generation	Uncovered Generation	Loss in Transmission Utilization
	MW	MW	MW	MW	MW
0.74	500	370	340	160	118
0.069	1000	69	573	427	29
0.01	1500	15	795	705	7
	Total (MW)	454(15%)		Total (MW)	155(5%)

Notes

1. We assume 6 units of 500 MW each in the IGCC+CCS plant and the ACWH project. The probability of an outage of a certain capacity is based on the forced and maintenance outage rates of individual units. For example, the probability of outage of 1,000 MW is the probability of two generation units being down simultaneously. We also assume that maintenance outages are distributed to avoid large outages, implying that the units are taken down for maintenance one at a time.

2. The loss in generation due to an outage depends on the profile of wind generation. For example, if an outage of 500 MW occurs, the loss in generation will be minimal if the backed down power generation capacity is at least 500 MW or more. This will be the case if wind is producing at least 500 MW more. Backed down power generation is estimated based on the profile of wind generation.

2. Improved Utilization of the G+CC+CCS Plant in the ACWH Configuration

For a stand-alone IGCC+CCS plant, an outage of a power generation unit (forced or planned) requires the backing down of the gasifiers, which reduces the utilization of not only the gasifiers but also of the other components of the plant such as the air separation units, pollution control equipment, and carbon separation and capture equipment. In the ACWH configuration, this is not the case because most of the time, the generation capacity that is unavailable due to an unforced or a planned outage is lower than the backed down generation capacity which can be ramped up to cover loss of generation due to an outage. If an outage occurs when not enough capacity is backed down which can be ramped to cover the outage, the output from the gasifiers can be diverted to the fuel production or the storage facility. The forced outage rate of combined cycle power generation units in a stand-alone advance coal plant (IGCC+CCS) and the ACWH is about 2%, hence the utilization of the rest of the G+CC+CCS plant (except the power generation unit) is 2% higher in the ACWH compared to a stand-alone IGCC+CCS plant.

3. Avoiding Wind integration Costs and Additional Capacity Credits

Compared to a stand-alone wind plant with variable output, the output from the ACWH plant is firm and relatively constant. Hence wind generation included as part of the ACWH plant does not impose any wind integration costs on the system. Also, the ACWH plant offers substantially more capacity towards meeting resource adequacy requirements compared to a stand-alone wind project.

Additional Costs of the ACWH Configuration

1. Lower Capacity Factor of the Power Generation Units

Even though including a fuel production or storage facility in the ACWH configuration enables full utilization of most of the components of the G+CC+CCS plant, the power generation unit (CC), needs to backed down to accommodate wind generation. This increases the fixed costs of generation per unit of electricity produced.

2. Higher Variable Fuel Costs due to Lower Heat rate

Compared to a stand-along coal plant, the power generation unit in the ACWH operates at a lower capacity factor, which increases its heat rate by about 3%. This higher heat rate results in slightly higher variable costs of production.

3. Additional Costs of the Fuel Production or Storage facility

The fuel production plant in the ACWH configuration operates at a lower capacity factor compared to a fuel plant in a stand-alone fuel production facility increasing the fixed costs per unit of fuel produced. ACWH with a syngas storage facility incurs costs of syngas storage.

Appendix B. Supply Side Options Not Considered in This Analysis

In this Appendix, we discuss the rationale for not including certain supply side options in our study.

Plants Using Wyoming Coal in Other Locations

Coal from Wyoming can be railed to a location near the load center where an IGCC+CCS plant can be constructed. Alternatively, syngas produced from gasifying Wyoming coal can be transported via pipeline to the load center where it can be used in a combined cycle power plant. The optimal location of plants using Wyoming coal will depend on the relative cost of transporting electricity, coal, and CO_2 which depends on the plant's distance from the load center, coal mines, and the CO_2 sequestration sites (for an IGCC +CCS plant located near the load center). Analyzing optimal choices for locating plants using Wyoming coal in beyond the scope of this study. However, the methodology used in this study would be applicable to other sites.

Nuclear Power

We did not analyze nuclear power in this study because it has significant legal and environmental constraints in some of the states with large load centers (e.g. California law[38] precludes additional nuclear power until nuclear waste and disposal issues are resolved).

Natural Gas Combined Cycle with Carbon Capture and Sequestration

We do not consider this option because other studies have estimated that the cost of saved CO2 emissions is ~$80/Ton of CO_2 (NETL, 2007a). For the emission allowance prices considered in this analysis, the more economical option is a natural gas plant that buys emission allowance permits.

IGCC Coal Plant Without CCS

We do not consider an IGCC plant without CCS as a competing option since it is more expensive than a PC plant. Without CCS, IGCC does not offer economic advantages over a PC plant. IGCC has lower sulfur and mercury emissions and also has lower water requirements compared to a PC plant. However, monetizing the benefits associated with reduced sulfur and mercury emissions and water requirements is beyond the scope of this study; hence we do not consider an IGCC without CCS as a competing option.

Biomass

We do not consider biomass-based generation as an option primarily because estimating the cost of biomass generation involves estimating the price of biomass as a fuel which is

[38] See California Public Resources Code 25524.1 (a) (1), 25524.1 (b), and 25524.2 (a)

beyond the scope of this analysis. Also the emission allowance cost incurred by biomass generation depends on the whether or not biomass is considered a carbon neutral fuel which depends on the level of fossil energy input in the production of biomass. Analyzing the CO2 emission associated with biomass based generation is also beyond the scope of this analysis.

Geothermal

We do not consider geothermal generation as a competing option because the geothermal option is geographically limited given current technology.

Concentrating Solar Power (CSP)

CSP produces most of its power during the day hence is comparable to an intermediate or peak load plant. In this study, the competitiveness of the hybrid and other options is analyzed for meeting base-load requirements. This is because we believe that the hybrid option will be most competitive as a base-load resource. Hence, we do not consider CSP in this analysis.[39]

[39] Unlike a CSP plant, a wind plant produces power during all hours of the day which is similar to a base-load plant and hence we consider it as a competing option in our analysis.

Appendix C. Rationale for the Size of ACWH and Competing Options

In this appendix, we discuss the rationale for selecting a particular size of the ACWH and competing options. We consider ACWH options at a scale where most of the economies of scale are accrued. For a G+CC+CCS plant, most of the economies of scale are accomplished for a size of about 1,000 MW. Transmission exhibits substantial economies of scale up to a much larger capacity. For example, a 3,000 MW, 500kv HVAC line is about 20% cheaper (per MW-mile) than a 1500 MW, 500kv AC line.[40] Economies of scale in building transmission capacity do exist beyond 3,000 MW but they are not as significant. Hence the ACWH configurations analyzed in this study consist of a 3,000 MW transmission line and a 3,000 MW G+CC+CCS plant. Similarly all the competing options considered in our analysis have a rated capacity of 3,000 MW.

With a larger transmission capacity, the cost of transmission per MW-mile may drop lowering the per unit cost of transmission. This may reduce the benefits of improving transmission utilization and hence the attractiveness of an ACWH option.

Size of a Wind Plant in the ACWH Configuration

In order to accommodate wind generation, the power generation units in the G+CC+CCS plant in the ACWH project need to back down which increases their heat rate. This increase is more drastic when the power generation units are backed down beyond about 50% of their capacity. The ramp rate requirements of the power generation units to accommodate wind generation also introduce constraints on how they are backed down. For example, consider a case where 50% of the capacity of a 3,000 MW combined cycle plant needs to be backed down. If this power plant consists of six power generation units of 500 MW each, one option for backing down 1,500 MW would be to shut down three out of the six units. However, when the wind generation drops, the power plant needs to quickly ramp up its generation, which is not possible if some of its units are shut down and the other units are operating at their full capacity. Given the ramp rate constraints, a viable option is to back down each of its power generation units to 50% of their capacity. The backing down of the power generation units is also limited by their minimum generation requirements. Given these constraints, we consider a 1,500 MW wind generation plant in our ACWH configuration, which implies that the power generation units are backed to 50% of their capacity when the wind plant is producing its maximum output.[41]

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[40] Estimates based on the transmission costs reported in the report "*Frontier Line Analysis of Transmission Links and Costs to be Used by the Economic Analysis Subcommittee (12/1/2006)*" by the Western Regional Transmission Expansion Partnership, Transmission Subcommittee.

[41] It is possible to include a wind plant larger than 1,500 MW in the hybrid configuration. Theoretically, the hybrid can have 3,000 MW of wind plant. However, this would reduce the economic benefits of the hybrid configuration in the following two ways: First, the heat rate of the power generation units will be reduced substantially. For example, there will be instances when the power generation units are operating below 20% of their rated capacity which substantially increases their heat rate. Second, in cases where the wind output is above a certain level, some of the power generation units would need to be shut down when the

Size of the Fuel Production Facility in the ACWH Configuration

When the wind plant is producing maximum output, only half of the gas produced by the gasifiers is used for power generation and the other half is used in the fuel production facility. Hence the fuel production facility needs to have a capacity which can process gas that otherwise would have produced 1,500 MW of power.

Rationale for Wind Capacity Overbuild

Given the large distance between Wyoming wind sites and load centers in California, Arizona, and Nevada, power transmission costs are significant and so are the benefits of improving the utilization of the transmission lines. One option to improve the utilization of transmission lines in a stand-alone wind generation option is to overbuild the capacity of the wind plant compared to the capacity of the transmission lines. The improvement in transmission utilization with wind capacity overbuild depends on the profile of wind generation.

Table C-1 shows estimates of improvement in the utilization of transmission capacity (TC) with 20% wind capacity overbuild for wind generation at different sites.

Table C-1. Wind Capacity Overbuild and Transmission Utilization

		TC Utilization		
Location	Data source	Original	Overbuild	%Increase
DaveJohnson	FEAST	48%	53%	10%
Bighorn	NREL	37%	42%	15%
NW	NREL	29%	34%	18.8%
MN	NREL	41%	48%	16.5%

The improvement in transmission utilization varies across sites, which implies that the benefits associated with overbuilding wind capacity will also very significantly. For the stand-alone wind generation option, we analyze the cost effectiveness of overbuilding the wind capacity by 20%. Based on the analysis of the modeled wind generation data from the Bighorn basin in Wyoming, we estimate that wind capacity overbuild of 20% will improve the utilization of the transmission lines by ~15%. We also assume that the wind generation that cannot be sent through the transmission lines can be sold locally in Wyoming. Levelized cost of electricity from a wind plant operating at a 47% capacity factor will be about $50/MWh if the power is sold locally and are about $80/MWh for a PC plant, assuming high carbon emission allowance costs. Even if we assume that the carbon emissions price will be 50% lower than that assumed in the Base Case, the levelized cost of electricity from a PC plant will be about $60/MWh. Hence we assume

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power plant needs to be backed down below a certain percentage of its capacity. These units need to be turned back on again when the wind generation drops, which will impose costs associated with the starting these units. If the units cannot be started fast enough, maintaining a combined output of 3,000 MW is not possible. This implies a lower utilization of the transmission lines and some intermittency in the output of the hybrid configuration; both of these reduce the economic benefits associated with the hybrid configuration.

that wind generation will be competitive in Wyoming and can at least fetch a revenue of $50/MWh. Given these assumptions, we find that it is economical to overbuild wind capacity by 20%. Hence for the stand-alone wind generation option we consider, we assume that the wind capacity will be overbuilt by 20%.

Appendix D. Cost and Performance Assumptions of ACWH and Competing Options

In this appendix, we provide information on the key cost and operating performance characteristics of the ACWH and competing options (see Section 4). These include input assumptions related to generation (section D.1), fuel production and syngas storage (section D.2), carbon transport, geologic storage, and EOR revenues (section D.3), fuel prices (section D.4), CO2 emission allowance prices (section D.5), costs related to variable wind generation (section D.6), and transmission (section D.7).

D.1 Cost and Performance Assumptions Related to Electricity Generation

Heat Rate

Heat rate estimates for the PC and IGCC+CCS plants are for power plants in Wyoming using PRB coal and take into account the effect of higher elevation in Wyoming. Heat rate for the G+CC+CCS plant in the ACWH configuration is higher than that of the stand alone IGCC+CCS plant because the power generation unit in the G+CC+CCS plant in the ACWH configuration is operated at an average capacity factor of 70% instead of 85% as in the case of a stand-alone plant. This increases its heat rate by 3% compared to a stand alone IGCC+CCS plant. The heat rate assumed for the NGCC is for a generic plant at lower altitude than Wyoming.

Capacity Factor

We estimate the maximum capacity factor for each generation option in order to meet baseload requirements; this approach is driven by the economic screening approach of estimating levelized costs.

ACWH Options

<u>ACWH Without a Fuel Production or a Syngas Storage Facility</u>

In this ACWH configuration, the entire G+CC+CCS plant is backed down to accommodate wind generation, which lowers its capacity factor. We adopted the following assumptions to derive the capacity factors: a 3,000 MW G+CC+CCS plant and a 1,500 MW wind plant connected to a 3,000 MW transmission line. A 1,500 MW wind plant operating at 47% capacity factor produces 6,176 GWh of electricity in a year, which is equivalent to the electricity produced by a 3,000 MW G+CC+CCS plant operating at a 23.5% capacity factor. Hence the capacity factor of the 3,000 MW G+CC+CCS plant will be reduced by 23.5% to accommodate wind generation from a 1,500 MW wind plant operating at 47% capacity factor. This would mean that if the capacity factor of a stand alone G+CC+CCS plant is 85%, then the capacity factor of that plant in a hybrid configuration will be 85% - 23.5% = 61.5%. However, this calculation does not take into account the fact that the power plant needs to be backed down by the capacity which is already not operational due to various types of outages (e.g. forced, planned maintenance oautage). For example, if the wind generation is 700 MW and a 500 MW unit is already not in operation due to an outage, then only 200 MW of additional capacity needs to be backed down instead of backing down 700 MW. If we take into account the probability of different sizes of outages in generation capacity (e.g., probability of a 500-1,000 MW generation capacity outage) and estimate the capacity that needs to be backed down beyond what is already down by an outage, the required reduction in capacity factor of the 3,000 MW IGCC+CCS plant is 14.1%, rather than 23.5% to accommodate wind generation. Hence the capacity factor of the IGCC+CCS plant is estimated to be 70.9% (85% -14.1%).

<u>ACWH with Fuel Production or Syngas Storage</u>

In an ACWH configuration with a fuel production or a syngas storage facility, the rest of the G+CC+CCS plant is utilized at its maximum capacity, except the power generation unit. In these configurations, the capacity factor of the power generation unit will be the same as that in the case of an ACWH without a fuel production or a syngas storage facility. However, the capacity utilization of the rest of the G+CC+CCS plant is higher for an ACWH configuration with a fuel production or a syngas storage facility compared to an ACWH configuration without a fuel production or a syngas storage facility. Except for the power generation unit, the rest of the plant can operate at full capacity since the syngas that is not used for power generation can either be used for fuel production or can be stored.

The capacity utilization of the rest of the plant in a ACWH with a fuel production or syngas storage facility is higher even compared to a stand alone IGCC+CCS plant because, for a stand alone IGCC+CSS plant, a forced outage of a power generation unit would require backing down the gasifiers in the plant, which reduces the utilization of the rest of the IGCC+CCS plant. This will not be the case in a ACWH configuration with a fuel production or a syngas storage facility since the syngas that can not be used by the power generation unit which is down can either be used in a fuel production facility in a ACWH with a fuel production facility or can be stored in a hybrid with a syngas storage facility. Hence the utilization of the rest of the system will be about 2% higher (which is the forced outage rate of a power generation unit) in a hybrid configuration with a fuel production or syngas storage facility compared to a stand alone IGCC+CCS plant.

Competing Options

<u>Stand-alone IGCC+CCS Plant</u>

We assume a capacity factor of 85% for a stand-alone IGCC+CCS plant based on estimates provided by NETL.

<u>Wind</u>

Wyoming has many areas with high quality wind. We assume that the wind plant considered in this study will be located in the Dave Johnson area which has approximately 60,000 to 70,000 MW of wind generation potential with class 6 and class 7 wind resources. The expected capacity factor (in 2015) for a wind plant with a class 6 wind resource is 47% (DOE, 2007); this is the wind capacity factor used in our Base Case scenario.

<u>PC & NGCC</u>

The outage rate (forced + maintenance) for NGCC and PC plants is about 10%; hence we assume a capacity factor of 90% for these plants.

D.2 Additional Cost of Fuel Production or Syngas Storage in ACWH Configurations

Additional Cost of Fuel Production

In the ACWH options with a fuel production facility, the output of the fuel production facility varies proportionately to the output of the wind plant. For example, when the wind output is at its maximum (i.e., 1,500 MW), the power generation units are backed down to about 50% of their capacity and thus utilizes only about half of the syngas produced by the gasifiers. The remaining output from the gasifier is supplied to the fuel production facility. In this situation, the fuel production facility is operating at its maximum capacity. Alternatively, when the wind output is zero, the power generation unit is producing at its maximum capacity and utilizes all of the syngas produced by the gasifiers. In this situation, the fuel production facility is not producing any fuels. As a result, the capacity factor of the fuel production facility in the hybrid configuration is equal to capacity factor of the wind plant (47%), which is lower than the expected capacity factor of a stand-alone fuel production facility. The lower capacity factor of the fuel production facility increases the fixed cost per unit of the fuel produced.

Our analysis recognizes that this incremental increase in fixed cost in fuels production is incurred to transform variable output wind into constant power output. Table D-1 shows the extra cost of fuel production facilities for hybrid options with syncrude and SNG production facilities. We make an accounting adjustment to attribute this cost to power generation in the hybrid facility. For example, in the ACWH configuration with a syncrude production facility, the capital cost of the FT reactor (i.e., a reactor which converts syngas to syncrude) that has a peak capacity of handling gas which otherwise can be used to produce 1,500 MW is $799 million. However, this FT reactor operates at a 47% capacity factor. The capital cost of a FT reactor which operates at its maximum capacity factor most of the time and produces the same amount of syncrude is $376 million. Hence the extra cost of the FT reactor due to a lower capacity factor is $424 million. We allocate this cost to the cost of power production, which translates into an additional cost of $1.4/MWh.

Table D-1. Extra Fuel Production or Storage Costs

ACWH	**Additional Cost ($ Million)**	**Averaged Over Total Generation ($/MWh)**
Syncrude	424	1.4
Synthetic Natural Gas (SNG)	358	1.3
Syngas Storage	380	1.3

Cost of Syngas Storage

Adding a syngas storage facility can also increase the utilization of the ACWH plant. In this configuration, all the other components of the G+CC+CCS plant are sized lower than the power generation unit. The gasifiers (and other components of the ACWH plant) are operated at their peak capacity most of the time and produce enough syngas (over time) to power a 3000 MW power generation unit operating at about 70% capacity factor.[42] Whenever the power output from the G+CC+CCS plant needs to be more than 2,295 MW (i.e., when the wind plant is producing below its average output of 705 MW), the cleaned up syngas from a storage facility will be utilized for powering some of the generation capacity. For example, if the power plant is operating at 3,000 MW (which is the case when the wind output is zero), the syngas for producing 2,295 MW is provided by the gasifiers and the syngas required to power the remaining 705 MW is obtained from the storage facility. Alternatively, whenever the power generation unit is producing below 2,295 MW, the syngas gas not utilized for power generation is stored. With this configuration, only the power generation unit needs to be backed down to accommodate wind generation and the rest of the plant is utilized at its full capacity.

The amount of syngas storage required in this option is influenced by the variation in wind output. The longer this time period, the greater is the storage requirement. We analyzed annual time series data of hourly wind generation for many different sites and found that the intra-day or intra-month cumulative deviations of wind generation from its mean value do not impose as large a storage requirement as the inter-month (seasonal) deviations. Wind generation in Wyoming (e.g., wind data from the Bighorn Basin) shows a clear seasonal pattern. The monthly wind generation in summer months is consistently less than monthly average wind generation based on annual data, while wind generation is higher during winter months compared to monthly averages for wind generation based on annual data. Hence during the winter months, syngas is stored and during the summer months, it is taken out of storage. Table D-2 shows the seasonal pattern in wind generation and the use of storage each month (negative sign indicates that syngas from storage is utilized for power generation). The storage is expressed in terms of electricity that can be produced (GWh) from the syngas stored. As seen in Table D-2, the cumulative withdrawal from storage during the summer months (June to October) is 491 GWh which is approximately equal to the storage requirement (i.e., syngas that is required to generate 491GWh will have to be stored).

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[42] If we assume that one unit of gas is required to generate 1 GWh, a 3,000 MW plant operating at 70% capacity factor will need 18,396 units of gas. Hence the gasifiers (which have 85% availability) need to have a capacity of to power 2,470 MW to produce the same amount if syngas.

Table D-2. Syngas Storage Requirement

Month	Generation (GWh)	Storage Requirement [Monthly Average - Monthly (GWh)]
Jan	398	-13
Feb	586	214
Mar	477	66
Apr	397	-1
May	424	13
Jun	358	-40
Jul	300	-112
Aug	305	-106
Sep	252	-146
Oct	304	-108
Nov	550	152
Dec	472	60
Maximum Cumulative Storage Requirement		**512**
Storage as a % of Total Generation		**11%**

The seasonal pattern of wind generation varies year to year, which will affect storage requirements which needs to be adequate for meeting storage requirements in years where monthly wind generation output varies the most. We examined sites with multiple years of wind output data and estimated the storage requirements for each year. Table D-3 shows the yearly storage requirement as a percentage of total generation in three consecutive years for wind sites in Minnesota (MN) and Pacific Northwest (NW). The year to year variation in storage requirement, defined as the standard deviation of the storage requirement, is relatively small as a percentage of total generation.

Table D-3. Year to Year Variation in Storage Requirement

Storage Requirement (% of Total Generation)				
Year	1	2	3	Stdev
MN	5.79%	6.42%	4.70%	0.70%
NW	7.0%	6.8%	7.7%	0.38%

We estimate the syngas storage requirement for an ACWH plant in Wyoming, using wind generation data from the Bighorn Basin. Because we only have one year of wind generation data for Bighorn Basin site, we assume that the year-to-year variation in storage requirement for wind generation sites in Wyoming is similar to that of MN and Pacific Northwest sites. We assume that the standard deviation of the year to year variation in storage requirement for wind sites in Wyoming is equal to the average of the standard deviation of the year to year variation in storage requirements for wind sites in MN and NW, which is 0.54 (expressed as a percentage of the total yearly generation). For the Bighorn Basin site, the storage requirement is 11% of the total generation based on one-year time series wind generation data. We assume that the observed storage requirement for our particular year (11%) is two standard deviations below the mean yearly storage requirement and estimate the storage capacity requirement by estimating a value, which is two standard deviations above the mean storage requirement. Hence the estimated storage capacity requirement is four standard deviations above the observed value, which leads to an estimate of storage requirement of 14% of the total wind generation in a year. For a 1,500 MW wind plant operating at 47% capacity factor, it is 892 GWh, which translates into a syngas storage requirement of 107 Million Kg of Syngas (0.12 Million Kg of Syngas is required to produce one GWh)

<u>Storage Costs</u>

The syngas used for power generation primarily consists of hydrogen. The most cost effective method to store hydrogen is by underground storage (NREL 1998). Among underground storage options, using abandoned natural gas wells is the cheapest alternative, followed by solution salt mining, and hard rock mining. The cost of storage ranges from $2.5/Kg to $18.9/Kg of hydrogen. The operating cost of hydrogen storage ranges from $1/Kg to $3.5/Kg. Powder River Basin has numerous pressured gas reservoirs that are reaching the end of their lives. These structures would be compatible with the injection and withdrawal of syngas. We use the lower bound of the cost estimate for storing hydrogen from the NREL study since it represents storage costs for depleted natural gas wells. Applying these cost parameters yields an estimate of $380 million for the total cost of the storage facility.

D.3 Costs of Carbon Transport and Geologic Storage and EOR Revenues

The cost of transporting CO2 is about $0.8/ton of CO2 per 100 miles given the scale of CO2 transport required for a 3,000 MW G+CC+CCS plant (IPCC, 2005). There are many potential sites for sequestering carbon within 200 miles of the proposed location of the IGCC+CCS plant in Wyoming. Assuming 200 miles from the plant to the sequestration site, the cost of transporting CO2 is $1.6/ton.

The cost of geologic storage ranges from $0.5/ton to $8/ton of CO2 (IPCC, 2005). The lowest storage costs will be associated with onshore, shallow, high permeability reservoirs and/or the reuse of wells and infrastructure in disused oil and gas fields. When storage is combined with enhanced oil recovery (EOR), enhanced gas recovery (EGR) or enhanced coal bed methane recovery, the benefits of enhanced oil or gas production can offset some of the capture, transport, and storage costs.

The revenues from EOR depend on the price oil; the value of EOR increases with the value of recovered oil. Table D-4 shows the relationship between the price of oil and EOR revenues. There are different possibilities for sharing of EOR revenues between power producers and oil producers. If we assume a bilateral monopoly, the revenues from EOR are likely to be shared in half which means that the power producer will receive $19.5/ton of CO2 ($18/MWh) at an oil price of $50/bbl.

Table D-4. Oil Price and EOR Revenues

Oil Price ($/BBl)	30	50	70
EOR Revenue ($/Metric Ton)	23	39	54
EOR Revenue ($/MCF)	1.2	2	2.8
EOR Revenue ($/MWh)	**22**	**36**	**51**

Source: DOE (2006)

Although there is substantial experience in using CO2 for EOR, there is limited understanding of the ability of the oil and gas fields to store CO2 over a long time period (a century or more).

EOR Potential

A 3,000 MW IGCC+CCS or G+CC+CCS plant operating on PRB coal will capture 710 million tons of CO2 over its lifetime (assuming a 30 year lifetime and a capacity factor of 85%). The total economic potential for EOR in the Rocky Mountain region is 500 million tons of CO2 (DOE, 2006). Therefore, the EOR market in the Rocky Mountain region will be fully saturated by about 70% of the emissions produced by the advanced coal facility. The rest of the emissions can be sequestered in other geological formations which have a large potential for storing CO2. However, in this case, the power producer will incur the costs of transportation and storage. Alternatively, the captured CO2 can be transported to more distant states where there is potential for EOR. Table D-5 shows EOR revenues net of associated transportation costs.

Table D-5. Carbon Transport Cost and Net EOR Revenue

CO2 Trasnport	Distance (Miles)	EOR Revenue ($/Ton CO2)	Transportation Costs ($/TonCO2)	EOR Revenue ($/TonofCO2)	EOR Revenue ($/MWh)
Within Rocky Mountain Region	200	19.5	1.61	18	19
To Regina, SK	500	19.5	4.03	15	16
To Calgary, AB	770	19.5	6.20	13	14
To Odessa, TX	1020	19.5	8.21	11	12

Note:

1. EOR revenues for a bilateral monopoly case for an oil price of $50/bbl

2. We assume a transportation cost of $0.8/Ton of CO2 per 100 miles (IPCC, 2005)

For all the locations shown in Table D-5, the EOR revenues more than offset the cost of transport and geological storage (given that geological storage costs range from $0.5 to $8/ton of CO2). Hence it is reasonable to assume that the costs incurred for transporting and storing CO2 are likely to be more than offset by EOR revenues, even at an oil price of $50/bbl. Given the current oil prices, the net EOR revenues would be much higher than those estimated in Table D-5 a bilateral monopoly case. However, it is not clear whether the CO2 market will be a bilateral monopoly. If there are more than one competing suppliers of CO2 whose CO2 supply is a substantial portion of the CO2 storage potential for EOR, then the share of revenue obtained by the CO2 suppliers (in our case, the power producer) is likely to fall drastically. Alternatively, if there is more than one competing buyer, the share of EOR revenues obtained by the power producers might more be compared to a bilateral monopoly case. Given the limited potential for EOR, the former is more likely to be the case. Given the uncertainty surrounding the EOR revenues obtained by the power producer, for our Base Case, we make a conservative assumption that EOR revenues are only sufficient to offset the cost of CO2 transport and geological storage. We analyze the sensitivity of our results to the assumptions about EOR.

D.4 Fuel Prices

Natural Gas Prices

Large uncertainty surrounds the prices of natural gas in the future. Numerous entities forecast natural gas prices. Natural gas price projections by the Energy Information Administration presented in its Annual Energy Outlook (AEO) and NYMEX natural gas futures market prices (for five years) are commonly used sources for future natural gas prices. We use a combination of the information available in AEO forecasts and NYMEX futures prices to project natural gas prices during 2015-45.

Where available, we use NYMEX futures prices for two reasons. First, NYMEX futures prices are likely to include the effect of the risk premium paid to have price certainty in the future. When gas-fired generation is compared with renewable energy generation or other technologies with minimal fuel price risk, it is appropriate to use firm (or locked in) natural gas prices (i.e., NYMEX futures prices) in order to make the fuel price risk comparable.

Second, NYMEX futures prices are discovered in the market meaning that they are actual realized prices for natural gas sale in the future. For example, if October 2012 futures price is $7.0/MMBtu, one has an option of buying that futures contract and locking in that price. However, NYMEX futures prices are available only up to 2012.

For the period after 2012, various natural gas price forecasts can potentially be used to estimate natural gas prices beyond 2012. One option is to use the AEO forecast. However, for the last few years, NYMEX futures prices are higher than AEO projections. Bolinger & Wiser (2006) show that NYMEX prices are systematically higher than the AEO forecasts and argue that there are two possible reasons for higher NYMEX prices.

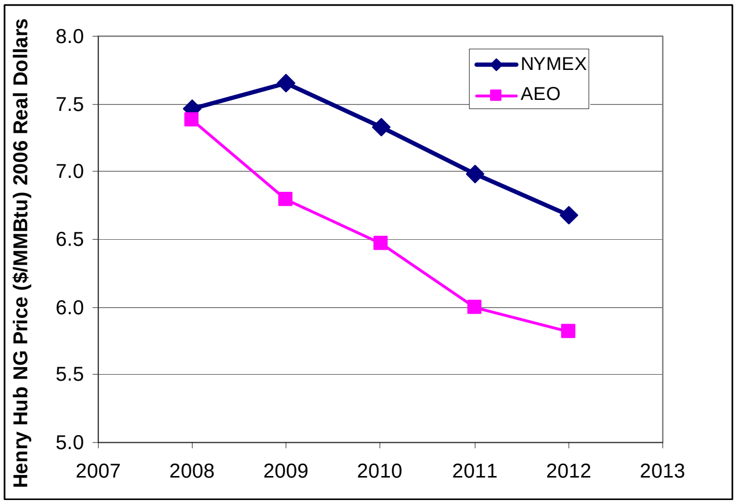

Figure D-1. Comparison of AEO and NYMEX Prices

First, NYMEX prices could include risk premium paid by the buyers to lock in future prices. Second, there could be systematic downward bias in AEO projections. One of the commonly used approaches for forecasting natural gas prices is to start out with a NYMEX futures price in 2012 and then project a price path which converges with the AEO price forecast in a few years. However, based on the comparison of AEO price forecast and NYMEX futures prices between 2007 and 2012, there is no evidence that the NYMEX futures prices are converging with the AEO price forecast and hence we do not take this approach.

An alternative approach is to essentially use the AEO price forecast by adjusting it upwards so that the relative difference between the corrected forecast and the original AEO forecast is the same as the difference between the NYMEX futures prices and the AEO forecast during the 2007-2012 period. We take this approach because it allows us to use the information available in the AEO forecast about the natural gas demand and supply situation in the future and also correct for the systematic downward bias or the exclusion of risk premium that the original AEO forecast might have compared to the NYMEX futures prices.

We undertake the upward correction to the AEO forecast as follows. We estimate a ratio of average yearly NYMEX futures prices and AEO forecast prices during 2007-2012. We use an average of this ratio to correct the AEO price forecast during 2012-2030. This approach assumes that the relative difference between AEO forecast and NYMEX futures prices during 2012-2030 will be the same as that during 2007-2012. The "adjusted" AEO forecast is for natural gas prices at the Henry Hub which differ from the delivered prices in the pacific region. We estimate the relative difference between the AEO forecast prices for Henry Hub and for the pacific region and use it to arrive at an adjusted gas forecast for prices in the pacific region.

Figure D-2 shows the original AEO Henry Hub natural gas price forecast, corrected AEO price forecasts using and NYMEX futures prices (on 08/23/2007) for 2007-2012. We are interested in natural gas prices during 2015-2045 and the AEO forecast is available only until 2030. We project natural gas prices during 2030-2045 by using the escalation rate during 2015-30.

Based on the prices projected using the methodology mentioned above, we estimate a levelized price of $7.35/MMBtu for our Base Case.[43] We do not claim that our Base Case assumption represents the best forecast of natural gas prices but we believe that it is a good starting point. We analyze the sensitivity of our results to assumptions about natural gas prices.

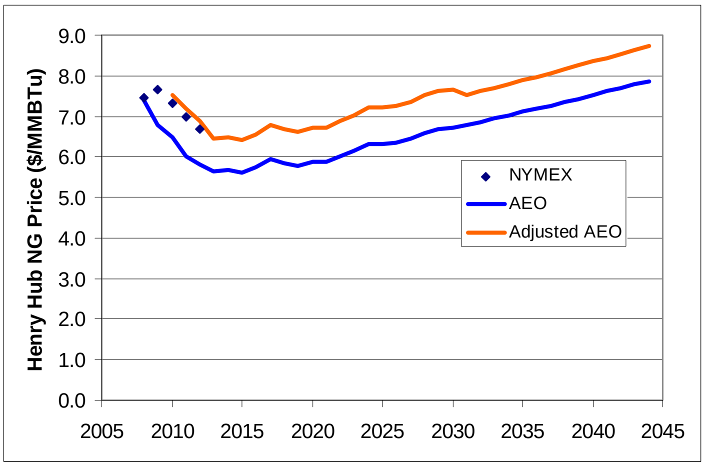

Figure D-2. Natural Gas Price Projections
Note: Prices in 2007 real $

Coal Prices

Coal prices have been far less volatile than natural gas prices. A key factor contributing to coal price stability is that coal is much easier to store than natural gas. Storage in the coal market serves to offset and reduce price swings causes by fluctuations in demand and short term supply constraints. We use the AEO 2007 forecast of coal prices. This analysis assumes the ACWH plant is located in Wyoming and utilizes PRB coal in Wyoming during the 2015-45 period. PRB coal is substantially cheaper than coal available in most other parts of the United States. The AEO forecast is available only until 2030; we project coal prices for 2030-45 period using the escalation rate in prices during 2015-30. The levelized price during 2015-45 is estimated to be $9.4/short ton, which does not include transportation costs because we assume that the ACWH plant will be a mine mouth power plant. We analyze the sensitivity of our results to assumptions of coal prices.

[43] All levelized prices are in 2007 dollars

D.5 Emission Allowance Prices

There is a general expectation within the electric industry that some type of federal carbon regulations will be adopted in the not-too-distant future (Barbose, Wiser, Phadke, & Goldman, 2008). Under many of the federal legislative proposals, carbon emission prices are projected to reach \$30-40/ton of CO_2 within the 2020-30 timeframe.

A coal plant coming online in 2015 will probably operate for thirty years until 2045. Hence the plant investment decision should account for emission allowance prices during 2015-45. However, most analyses of the federal legislative proposals project emission allowance prices until 2030. We expect that the emission allowance prices will rise above their 2030 levels during 2030-45 because most of the federal proposals mandate emission reduction beyond 2030.[44]

The EIA analysis of the latest McCain Lieberman proposal projects emission allowances prices until 2030. If we project them during 2030-45 using the same escalation rate in emission allowance prices during 2015-30, the emission allowance prices will reach \$140/ton of CO2 in 2045. However, we believe that the carbon prices will not rise continuously during 2030-45 since at some carbon price, most mitigation measures required for stabilizing CO_2 concentration at the desired level will be undertaken. Also there are likely to be political constraints on how much the carbon price can rise. Given these considerations, if we assume that the carbon price will not rise above \$80/ton, the levelized price during 2015-45 will be \$40/ton of CO_2. We assume a CO_2 emission price of \$40/ton for the Base Case. The Frontier Line Study also adopted a base case CO2 emission price of \$40/ton (WRTEP, 2007a). We analyze the sensitivity of our results to alternative emissions allowance prices.

D.6 Transmission Costs

For generation options located in Wyoming, we assume that a long distance transmission line will connect these resources to load centers in Southern California; costs for transmission options are based on assumptions used in the FEAST model. HVDC transmission lines have lower estimated costs than HVAC transmission, given the lengthy distances for these lines (see Table D-6). However, it is cheaper to have multiple tap points with HVAC transmission. For our Base Case, we assume a transmission line which is predominantly DC and has one more tap point in a load center (Southern Nevada) compared to the DC only transmission option.

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[44] For example, the latest McCain Lieberman proposal mandates emission reductions to 1990 emission levels during 2020-30 period, and reductions to levels 22% and 60% below 1990 levels during 2030-45 and 2045-and beyond, respectively. These reductions are required to keep the carbon concentration levels in the atmosphere in the 450-550 ppm range.

Table D-6. Transmission Options and Assumptions

Route	Distance	Capacity	Type	Cost ($ Million)	M $/MW	Losses
Wyoming - Mona (Utah) - S. Nevada - Southern CA	1092	3000	AC	4300	1.43	8%
Wyoming - S. Nevada - Southern CA	1090	3000	AC & DC	3300	1.10	7%
S. Wyoming - Southern CA	850	3000	1-500 kV DC	2700	0.90	6%

For generation options near the load centers, we assume a transmission distance of 100 miles, transmission costs based on HVAC transmission, and a transmission loss of 2%. We analyze the sensitivity of our results to the assumptions of transmission options and costs.

D.7 Other Costs and Assumptions

Estimation of AFUDC

AFUDC is estimated using a cost of capital of 6.5 % and a plant technology-specific construction outlay schedule.

Income Taxes

The state of Wyoming does not have income taxes. Federal income taxes are based on an income tax rate of 35%, which is assessed on the outstanding equity (no accelerated depreciation assumed while estimating outstanding equity). Levelized income tax per year is ~0.2% of the capital cost.

Property Taxes

Under Wyoming law, there are a variety of ways to assess property (Chapter 7, Department of Revenues rules). The most likely method for valuing a new plant would be based on replacement cost which should consider depreciation. The assessment is based on the value of the property in the ground as of January 1 of each year. The state multiplies the value of the plant times 11.5% (the taxable value for all state-assessed property) to arrive at a taxable value. The state-derived taxable value of the plant is provided to the county where the plant is located. The county multiplies the taxable value times the applicable millage rate. County-wide millage rate in Campbell County in Wyoming (where the ACWH is likely to be located) was 62 mills. Hence the property taxes are estimated as Total Plant Cost *11.5% * 62 mills per dollar (or 6.2 cents).

Appendix E. Assumptions Specific to Stand-Alone Wind Generation

In this appendix, we discuss the assumptions specific to stand-alone wind generation options, which include the time of use value of wind generation, wind integration costs, and resource adequacy costs.

We estimate the difference in the value of wind generation and other dispatchable base-load resources due to the difference in the timing of their generation output to see whether it is necessary to take this factor into account in the economic screening analysis.

Generation during peak times is usually more valuable than that during off-peak times since the system marginal costs and electricity prices are usually higher during peak times. The average value of generation from dispatchable base-load plants will be roughly the same since they are producing the same amount of power during most hours of a year. Similar to dispatchable base-load resources, a wind plant produces power in most of the hours in a year; however, the quantity of power generated varies across hours. We expect that the average revenue per unit of generation will not be very different for a wind plant compared to other base load generation options since unlike peaking or intermediate load plants, a wind plant produces power during peak as well as off-peak hours. Figure E-1 shows the distribution of wind generation over different hours of the day based on wind generation data from two sites in Wyoming.

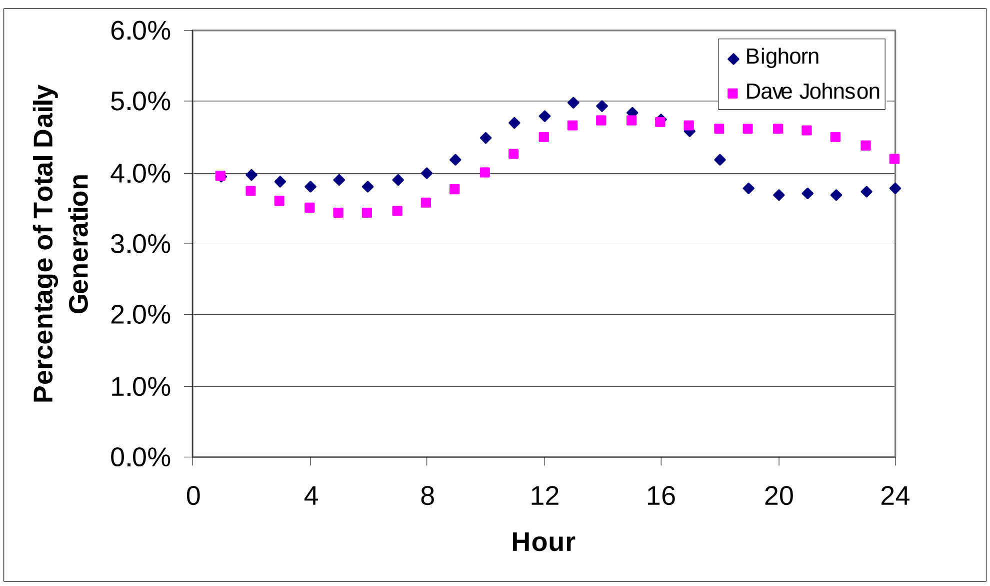

Figure E-1. Intra Day Distribution of Wind Generation

As Figure E-1 shows, wind generation is approximately evenly distributed during different periods of the day which also is the case for base load plants.

One way to analyze the effect of the difference in the timing of generation between base-load and wind plants is to value their generation at the system marginal cost for every hour and then compare the average revenue generated by these resources per unit of power produced. We use a year-long time series of hourly average CAISO real time prices (for 2006) on the path SP15 as proxy for system marginal costs. Figures E-2 and E-3 show the diurnal and seasonal variation in these prices.